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AUTHOR

COMPANY NAME Intuitive Research and Technology Corporation

COMPANY ADDRESS 5030 Bradford Drive
Building 2, Suite 205
Huntsville, AL 35805-1923

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14. ABSTRACT

Report on effort to establish full-spectrum crashworthiness criteria for implementation starting in the initial stages of system design for a wide range of rotorcraft classes, types, configurations, and operating conditions that continues over the life cycle of the rotorcraft system. This criteria will identify the key components that contribute to a systems crashworthiness and will provided a quantitative measure of crash performance. This document is not yet complete, with many sections still in outline format or with notional descriptions of how the criteria or Crashworthiness Index will be used. When complete, this will be a standalone document that evaluates all aspects of crashworthiness and ascribes a Crashworthiness Index to a system. Over the years, there has been repeated discussion about the need to revise crashworthiness design criteria and crashworthiness qualification methodology. As the DoD moves forward with the development of future systems and upgrades of current fleet helicopters, questions have arisen regarding the adequacy of existing specifications and guidelines. Guidelines do not exist to ensure crashworthiness of new generation rotary wing aircraft with broad ranges of gross weights. Many questions exist regarding the right criteria to apply to very large future generation rotorcraft. This document addresses the evolution of crash survival design criteria, its influence on rotary wing aircraft crashworthiness, and evolving technological applications to current and new-generation DoD helicopters. Emphasis is given to the need for a total system approach in design for crashworthiness and the need to consider crashworthiness early in the design phase of a new aviation weapon systems development effort.

15. SUBJECT TERMS
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Preliminary Rotary Wing Full Spectrum Crashworthiness Criteria

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Full Spectrum Crashworthiness Criteria

1. Scope

1.1 Purpose

To establish full-spectrum crashworthiness criteria for implementation starting in the initial stages of system design for a wide range of rotorcraft classes, types, configurations, and operating conditions that continues over the life cycle of the rotorcraft system. This criteria will identify the key components that contribute to a system's crashworthiness and will provided a quantitatve measure of crashworthy performance.

This document is not yet complete, with many sections still in outline format or with notional descriptions of how the criteria or Crashworthiness Index will be used. When complete, this will be a standalone document that evaluates all aspects of crashworthiness and ascribes a Crashworthiness Index to a system.

1.2 Background

Crashworthiness requirements for military rotorcraft are defined by MIL-STD-1290A (AV) which was cancelled in the mid 1990s but reinstated, without revision, in 2006. The Aircraft Crash Survival Design Guide (ACSDG) provided the basis for MIL-STD-1290. The ACSDG defines a set of crash scenarios that can be survivable if an aircraft is properly designed. This guidance significantly influenced the design of the AH-64 and UH-60 aircraft in the 1970's. Their performance in crash conditions have shown a great improvement over previous generation helicopters.

Over the years, there has been repeated discussion about the need to revise crashworthiness design criteria and crashworthiness qualification methodology. Over time, more mishap data becomes available; tactics, techniques and procedures change; new technologies are developed; and modeling and simulation capability improves. In addition, limitations of existing guidance become more evident. The ACSDG was first published in 1967 with revisions made in 1969, 1971, 1980 and lastly in 1989. MIL-STD-1290 was first published in 1974 and then revised in 1988. Aeronautical Design Standard (ADS) 36 was put together in the late 1980s and applied only to the Army Light Helicopter development program and has since been cancelled.

As the Department of Defense moves forward with the development of future systems such as Unmanned Aerial Vehicles (UAVs), Joint Future Theater Lift (JFTL), Joint Multi-Role (JMR) and upgrades of current fleet helicopters, questions have arisen regarding the adequacy of existing specifications and guidelines. The impact of future operations and environments and advanced design configurations on crashworthy design are not fully understood. Adequate guidelines do not exist to ensure crashworthiness of new generation rotary wing aircraft in these broad ranges of gross weights. Evidence also suggests that military helicopters are flying lower and faster than anticipated in the ACSDG, and that most crashes do not occur at Structural Design Gross Weight on prepared surfaces. Furthermore, past crashworthiness design guidance applied primarily to UH-60- and AH-64-sized and light fixed-wing aircraft. Work has been done to correlate helicopter size and mission to reasonable crash criteria, but it did not address very large rotorcraft and multiple impact surfaces. Many questions exist regarding the right criteria to apply to very large new generation rotorcraft such as the JFTL, Class IV and larger UAVs with expensive payloads, or any other rotorcraft not addressed by previous guidance and requirements such as MIL-STD-1290A. Even with current fleet helicopters, technology could be applied to improve crashworthiness over a range of crash impact surfaces (hard, soft soil and water), operating weights and pitch/roll attitudes. All attributes are tradable in a new aircraft design. There is difficulty in comparing crashworthiness qualities from one aircraft design to another. A comparative metric along with adequate tools need to be developed to apply a systems approach to crashworthiness at minimum cost and weight.

This document addresses the evolution of crash survival design criteria, its influence on rotary wing aircraft crashworthiness, and evolving technological applications to current and new-generation DoD helicopters. Emphasis is given to the need for a total system approach in design for crashworthiness and the need to consider crashworthiness early in the design phase of a new aviation weapon systems development effort. Consequently, effective crashworthiness designs must consider all likely sources of injury, eliminate or mitigate as many as practical for the given likely crash scenarios, and do so at an acceptable cost and weight.

1.3 Document Application

This Crashworthiness Criteria design document can be applicable to all rotorcraft systems throughout the life cycle of the rotorcraft.

2. Applicable Documents

2.1 General

There has been much research on crashworthiness in the last fifty plus years. Much of the design guidance contained in the ACSDG is still applicable and relevant. The requirements of MIL-STD-1290A, et al, are if anything, minimally acceptable requirements to be met.. There are also many specifications and standards that detail various subsystem requirements that will not be addressed by these criteria (e.g. seat standards, FAA standards, etc).

2.2 Government Documents

2.2.1 Specifications, Standards, and Handbooks

The following specifications, standards, and handbooks support this document to the extent specified herein. Unless otherwise specified, the latest issuances of cited documents shall be used unless otherwise approved by the assigned Technical Authority or as stated in the solicitation or contract.

2.2.1.1. JSSG-2010-7 – DoD Joint Service Specification Guide – Crew Systems Crash Protections Handbook

2.2.1.2. MIL-STD-1290A – Military Standard Light Fixed and Rotary-Wing Aircraft Crash Resistance

2.2.1.3. USAAVSCOM TR 89-D-22A – Volume I – Design Criteria and Checklists

2.2.1.4. USAAVSCOM TR 89-D-22B – Volume II – Aircraft Design Crash Impact Conditions and Human Tolerance

2.2.1.5. USAAVSCOM TR 89-D-22C – Volume III – Structural Crash Resistance

2.2.1.6. USAAVSCOM TR 89-D-22D – Volume IV – Aircraft Seats, Restraints, Litters, Cockpit/Cabin Delethalization

2.2.1.8. USAAVSCOM TR 89-D-22E – Volume V – Aircraft Postcrash Survival

(Copies of these documents are available online at http://assist.daps.dla.mil/quicksearch/ or www.dodssp.daps.mil or from the Standardization Document Order Desk, 700 Robbins Avenue, Building 4D, Philadelphia, PA 19111-5094.)

2.2.1.9. USAAVSCOM TR 90-D-16, *Development of Categorized Crashworthiness Design Criteria for US Army Aircraft*, Coltman, Simula, Inc. (May 1990).

2.2.1.10. AvCIR 62-9, *Military Troop Design Criteria*, Turnbow, AvCIR (Nov 1962).

2.2.2 Other Government Documents, Drawings, and Publications

The following other Government documents, drawings, and publications support this document to the extent specified herein. Unless otherwise specified, the issues of these documents are those cited in the solicitation or contract.

2.2.2.1. ARMY AVIATION OPERATIONS

TRADOC Pamphlet 525-7-15 – The United States Army's Concept Capability Plan (CCP)

2.2.2.2. AVIATION APPLIED TECHNOLOGY DIRECTORATE

Burrows, LeRoy T. - Paper No. 148 Proposed Revisions to MIL-STD-1290 Rotary Wing Aircraft Crash Resistance

(Copies of this document are available from the Proceedings of the Eighteenth European Rotorcraft Forum (US Army Aviation Systems Command, Avignon, France, 15-18 September 1992).

2.2.2.3. HEADQUARTERS, DEPARTMENT OF THE ARMY

Army Regulation [AR] 385-40 - Accident Reporting and Records

2.2.2.4. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA-STD-7009 - Standard for Models and Simulations

(Copies of this document are available online at http://standards.nasa.gov/public/public_query_NASA_stds.taf.)

This work was conducted under the Full Spectrum Crashworthiness Program for AATD.

2.2.3 Non-Government publications

The following documents support this document to the extent specified herein. Unless otherwise specified, the issues of these documents are those cited in the solicitation or contract.

2.2.3.1. AMERICAN SOCIETY OF MECHANICAL ENGINEERS (ASME)

ASME-V&V 10 - *Guide for Verification and Validation in Computational Solid Mechanics*

(Copies of this documents are available from or www.asme.org or ASME Information Central Orders/Inquiries, P.O. Box 2300 Fairfield, NJ 07007-2300.)

2.2.3.2. NATIONAL AEROSPACE LABORATORY

Ubels, L. C., and Wiggenraad, J.F.M. NLR-TP-2002-110, *Increasing the Survivability of Helicopter Accidents Over Water*, prepared for the First European Workshop on Survivability at Air Base Cologne-Wahn (Germany) by the National Luchten Ruimtevaartlaboratorium (National Aerospace Laboratory). February 2002

(Copies of this document are available from http://www.nlr.nl/smartsite.dws?lang=en&ch=DEF&id=65.)

2.2.3.3. UNIVERSITY OF LIVERPOOL, ENGLAND

Jones, N., and T. Wierzbicki - Structural crashworthiness and failure

(Copies of this document are available from the proceedings of the Third International Symposium on Structural Crashworthiness (14-16 April 1993), pp 1-511.)

2.2.3.4. OTHER

Shanahan, D.F.: Human Tolerance and Crash Survivability. Madrid, Spain, RTO-EN-HFM Lecture Proceedings No. 113, 2005, pp. 6-1 to 6-15.

2.2.4 Order of Precedence

In the event of a conflict between the text of this document and the references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

3. Definitions

This section provides definitions for specialized terms used within this document. Common use terms are provided in Appendix C.

3.1 Crash Avoidance – Crash avoidance can be viewed from two perspectives. The first is the prevention of mishaps. The second is the maintenance of aircraft control and energy management so that the potential crash is converted to a controlled event which is survivable. Crash avoidance is an important way to minimize injuries and aircraft damage but does not directly effect the crashworthiness of an aircraft, so avoidance systems are not within the scope of this document.

3.2 Crash Survivability- The ability of occupants , airframe and systems to survive crash impact forces, hazards and post crash hazards.

3.3 Crashworthiness

Ability of aircraft to maintain a protective space for occupants throughout the crash impact sequence; preventing occupants, cargo, or equipment from breaking free of their normal location and positions during a crash sequence; limiting the intensity and duration of accelerations experienced by occupants within affording some acceptable level of survivable trauma; preventing catastrophic injuries and fatalities resulting from contact with barriers projections and loose equipment; and limits the threat to occupant survival passed by fire, drowning, exposure, entrapment, etc., following the [post crash] impact sequence.

3.4 Crashworthiness Index

The Crashworthiness Index (CI) is a quantitative measure of a rotorcraft's crashworthiness across multiple crash environments and conditions. It is a single number calculation based on multiple crash conditions and a rotorcrafts performance in those conditions. (For example, a rotorcraft that crashes at x fps, with an impact angle of y degrees on z surface will have a CI f(x,y,z).) The CI is described in detail in section 5.5.

3.5 Crash Event Sequence (Impact Sequence)

The crash event sequence begins once the impact is inevitable. The crash event sequence ends once the vehicle has come to a rest and occupants, if any, have safely egressed.

3.6 Impact

The striking of one body against another; types of impact events include:

- Terrain: Event when a rotorcraft crashes on earth.
- Water Impact: Event when aircraft crashes on water. Definition may also include probability of crashing in a certain sea state.
- In-flight Impact: Aircraft impact into an obstacle above the earth's surface such as trees, wires, towers, vehicle and buildings. An in-flight impact could be followed by a terrain impact, a forced landing or a precautionary landing.

3.7 Rotorcraft

A rotorcraft is a heavier-than-air flying machine that uses lift generated by wings that revolve around a mast. The wings are referred to as rotor blades; a system of two or more blades on the same mast is referred to as a rotor or rotor system. Rotorcraft include helicopters, autogyros, gyrodynes and tiltrotors.

3.8 Rotorcraft Type

Rotorcraft have various design types that can have an influence on crashworthiness. These types include:

- Conventional rotorcraft (large main rotor with small tail rotor to mitigate torque)
- Tandem (two counter rotating rotors that are separated by a distance)
- Coaxial (Two counter rotating rotors in line with one another)
- Tilt Rotor (rotor systems that are capable of transitioning between providing vertical lift and forward thrust; also have a rigid lifting surface)

3.9 Rotorcraft Class Sizes (DGW)

Crash scenarios and rotorcraft performance are dependant on rotorcraft size due to scaling effects of structures and other various issues. Crashworthiness criteria will be differentiated between various rotorcraft classes as follows:

Class 0: < 8 lbs
Class I: 8 – 32 lbs
Class II: 33 – 200 lbs
Class III: 201 – 1500 lbs
Class IV: 1501 – 7500 lbs
Class V: 7501 – 75000 lbs
Class VI: > 75,000 lbs

3.10 Survivable Crash

An accident in which the forces transmitted to the occupant do not exceed the limits of human tolerance to abrupt accelerations and in which the structure in the occupant's immediate environment remains substantially intact to the extent that a livable volume is provided for the occupants throughout the crash sequence. These two criteria are applied to each occupant location in the aircraft. If all locations meet the criteria, the crash is "survivable." If one or more locations meets the criteria and one or more do not, the crash is "partially survivable." If none of the locations meet the criteria, then the crash is "non-survivable."

3.11 System Crashworthiness

Attributes of an aircraft design or a configuration that minimize occupant injuries and fatalities, aircraft and critical mission equipment damage throughout the entire crash impact sequence.

4. Applicability of Criteria

This criteria will be applicable to current and future rotorcraft systems. When evaluated under this criteria, any rotorcraft system will have a determinable crashworthiness index based on its system crashworthiness features and mission profile.

5. General Information

5.1 Integrated System Design Approach

An integrated system design approach to crashworthiness is a holistic approach to crash survivability design. The focus of crash survivability is on ensuring that the occupants survive the impact event and the time necessary for support to arrive (Section 5.2). Due to space weight and cost limitations, every component of a rotorcraft system is tradable. A cost-benefit analysis must show how each subsystem improves the overall system performance and is cost effective in crash and hard landing scenarios (Section 5.3). At the time of crash, crash survivability systems will be based on the following variables: the environment, the variability of operations, or flight regimes. The physical characteristics of the aircraft that inherently affect crashworthiness are weight at crash, rotor configuration, internal and external stores, etc. Each of these various components affect the overall crash survivability of the aircraft. By maximizing capability in each subsystem, and designing for the most probable crash events (while ensuring unlikely events can be assessed as well) a system design for full spectrum crashworthiness can be created. The extent to which a rotorcraft system incorporates the elements of crashworthy design (Section 5.4.1) to address mission considerations (Section 5.4.2), ensure post crash survival (Section 5.4.3) and improve crash avoidance (Section 1.1.1) using various technology solutions (Section 5.4.4), and the designer's ability to validate a design (Section 5.4.5) will all contribute to the rotorcraft system's score on the CI (Section 5.5). A minimally acceptable CI, as well as achievable CI and future growth CI requirements are also described (Section 6). Many of the conclusions and requirements are based on analysis of historical mishap data (Section 7) and current analysis of future operations.

5.2 Occupant Protection

5.2.1 Crash-Related Injuries

Injury in aircraft crashes can be considered to arise from three distinct sources: (1) excessive acceleration forces; (2) direct trauma from contact with injurious surfaces, and; (3) exposure to environmental factors such as fire, smoke, water, and chemicals resulting in burns, drowning, or asphyxiation. It has been estimated that approximately 85 percent of all aircraft crashes are potentially survivable without serious injury for the occupants of these aircraft. This estimate is based upon the determination that the crashes met two basic criteria. First, the forces involved in the crash were within the limits of human tolerance. Second, occupant's space remains substantially intact, providing a livable volume throughout the crash sequence. (NLR-TP-2002-110)

5.2.1.1 Primary Injuries

Injuries occur for many reasons and are dependant on location in the aircraft, terrain type, and protective systems used. When an occupant is in a crashworthy seat, the probability of spinal injuries decrease. When an occupant is not sitting, the risk of flailing injuries increase. Fatalities increase when an aircraft crashes during a cruise phase of a mission. Pilots are more likely to survive a crash event than passengers(This was not due to differences in spinal injury). Spinal injuries were found to be more common in pilots than non-pilots. Non –pilots were found to have more TBD injuries.

Survivability in a water impact seems to be dependant on two factors: Ability to egress (training and structural considerations for egress) and ability to remain cognizant (conscious).

5.2.1.2 Injury Mechanisms

5.2.1.3 Human Tolerance

5.2.2 Injury Assessment Technologies

5.2.2.1 System and Subsystem Testing

5.2.2.2 Anthropomorphic Test Dummy (ATD's) (Test Dummies)

5.2.2.3 Injury Assessment Risk Values (IARV's) (Risk Criteria)

5.2.2.4 Modeling

5.3 Crashworthy System Cost-Benefit Analysis

The occupant crash protection system defined in JSSG-2010-7 is required to eliminate injuries and fatalities in relatively mild impacts, and minimize them in severe, survivable mishaps. Minimizing personnel losses in crashes conserves the military's human resources, reduces medical and disability expenses, provides a positive morale factor, and thereby improves the effectiveness of the services both in peacetime and in periods of conflict. Military and civil research and field experience have shown that the initial cost and weight increases associated with incorporating crash protection features are offset by the cost-benefits of reduced personnel injury and reduced structural damage over an aircraft's life cycle. Consequently, new generation aircraft are now procured under a requirement to implement a systems design approach in the development of occupant crash protection.

A successful crashworthiness design is one that protects occupants from serious injury in potentially survivable crashes while limiting weight increase, costs, and additional maintenance to acceptable levels. Under-design of the system results in unexpected injuries and deaths while over-design of these elements result in unnecessary costs and weight. To avoid either eventuality, the author of the design specification, as well as the designer, should thoroughly understand:

1. Potentially survivable crash conditions and characteristics for the type of aircraft under consideration
2. Human kinematic response to input accelerations
3. Human tolerance to abrupt accelerations
   - Whole body
   - Regional (i.e., head, neck, abdomen, femur)
   - Human variability in anthropometry and impact tolerance
4. Injury mechanisms
5. Performance, weight, cost, and cost-benefits of crash protection features / subsystems

6. The affect of aircraft configuration / design features on aircraft crash response and occupant survivability potential

The most effective crash protective systems are ones where the design specifications were based on a correct prediction of the crash environment and an accurate assessment of human exposure limits.

Since a protective system cannot protect occupants in all crashes under all anticipated conditions, trade-off decisions have to be made in the development of protective system design specifications. In general, there are four inter-related factors that need to be considered in making these trade-off decisions.

- Anticipated survivable crash impact conditions (input variables) - velocity, force, attitude, environment, etc.
- Maximum acceptable injury level, and life cycle cost savings of reduced injuries and fatalities
- Host restrictions - space, weight, hard-point availability.
- Life cycle cost for all elements of the crash protective system.

The weight given to each factor depends on the particular aircraft application. When retrofitting a protective system into an existing aircraft, for example, host restrictions (integration constraints) and cost are usually the dominant factors since the new protective system must adapt to existing space and hard points, and costs are invariably fixed. In new aircraft designs, host restrictions are usually more flexible and can be adapted as necessary to accommodate the desired protection systems. However, in new aircraft programs the portion of available funds allocated to safety systems is not fixed, and safety and protective equipment must compete for weight and cost with all other aircraft systems. In this climate, program managers can be reluctant to trade performance for safety.

As implied above, cost and host restrictions tend to drive the decision making process in protective system implementation. However, the first two technical factors of the four listed above can easily be overlooked in the process. A thorough understanding of all four factors is absolutely imperative for making informed trade-off decisions.

Design of an appropriate protective system also requires an understanding of the crash and occupant survivability history for the specific aircraft application under consideration. This information can be estimated from a collective analysis of the crash history of similar class aircraft (i.e. type, size, gross weight, and mission) over an extended period of time. This analysis can then complement other analytical methods for determining the required crash protection envelope including impact velocities, attitudes, and surfaces.

Ultimately, the “right” level of crash protection for a particular application is determined by balancing the four crash design considerations cited above. Once that level has been determined, a systems approach is recommended for developing the crash protection system based on the principles provided in this document.

5.4 Design for System Crashworthiness

System crashworthiness is achieved, in part, as a result of crashworthy subsystems efficiently integrated to protect occupants and critical payload in a crash event. This section outlines design guidance and the processes necessary to quantify the safety characteristics of a crashworthy rotorcraft. Future rotorcraft designs may be slightly different from the types identified here (such as compound or co-axial types). Future developments are likely to focus on multiple roles for a rotorcraft. Though the designs may bring about new types of rotorcraft, the same basic design considerations for crashworthiness should be followed. In areas of special concern, the specific design should be evaluated with current crashworthiness technologies, so that the best crashworthy performance is obtained.

For this system level design approach, generic rotorcraft design types have been identified. The taxonomy implemented for the generic rotorcraft design types are: conventional, tandem, and tilt rotor, as shown in Figure 5.4-2. Key design dimensions of importance to the crashworthiness of the rotorcraft have been identified (Figure 5.4-3) along with nominal dimensions (Figure 5.4-2). These nominal dimensions can be scaled up or down, depending on the gross size of the rotorcraft. As in the case of the conventional rotorcraft, the nominal dimensions may be dependent on mission characteristics (**Figure 5.4-1).**

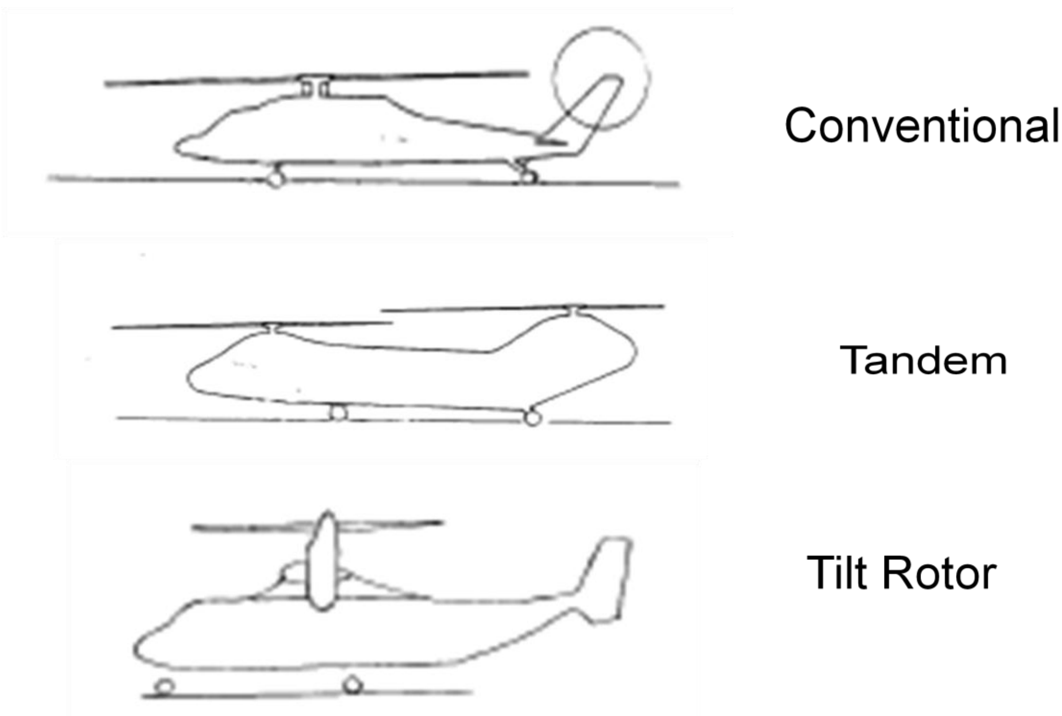


Figure 5.4-2 Generic Rotorcraft Design Type Taxonomy

The Conventional type covers a broad range of rotorcraft with different missions including attack, utility, and cargo. Although they all have a main rotor and tail rotor anti-torque the key design dimensions can be different due to mission requirements.

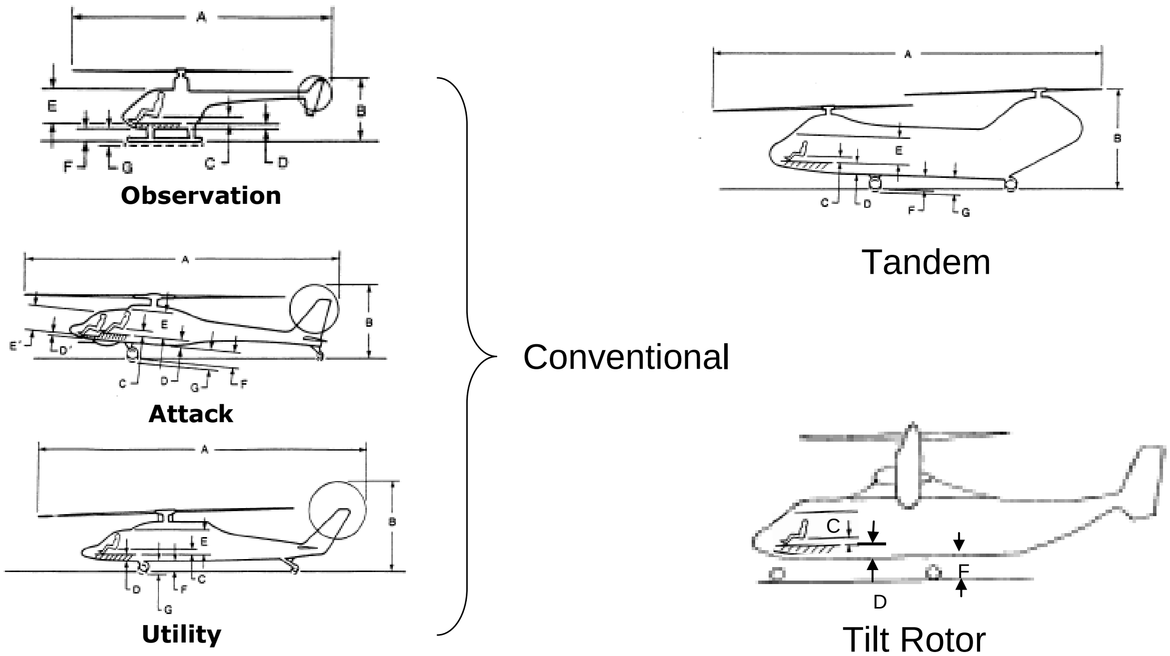


Figure 5.4-3 Generic Rotorcraft Types and Key Crashworthiness Design Dimensions

Some key design dimensions of importance to crashworthiness include: ground clearance, fuselage crush depth available, seat stroke available, type and location of landing gears, as well as overall rotorcraft height and length (Table 5.4-1). From these design dimensions, contributions to system crashworthiness of each subsystem is thus constrained by physical volume and energy attenuation technologies available to operate in that volume. To maintain occupant living space, location and management of high mass items play a key role.

Table 5.4-1 Generic Rotorcraft Types and Key Crashworthiness Design Dimensions

Generic Aircraft Configuration	Conventional (Attack)	Conventional (Utility)	Tandem (Cargo)	Tilt Rotor (Cargo/Assault)
Gross Weight (lb)	19,000	20,000	46,000	52,000
Design Dimensions (in)				
Seat Stroke	12.0	14.5	14.5	14.5
Subfloor Structure Crush Depth	17.0	15.0	24.0	16.0
Landing Gear Stroke	34.0	22.0	30.0	20.0

Based on these key design parameters, a spreadsheet can be developed to calculate the maximum vertical sink rate capability of the rotorcraft types shown in Table 5.4-2 using simple energy balance equations. The energy analysis was based on vertical impacts on a rigid surface. The results are shown in Table 5.4-2. The analysis assumptions regarding the load and efficiency factors typically achievable by the airframe, landing gear, and seats are shown in Table 5.4-3.

Table 5.4-2 Vertical Sink Rate Capabilities

	Landing Gear (fps)	Airframe (fps)	Total (fps)	Seat Stroke (in)
Conventional (Attack)	27.0	32.1	42.0	9.3
Conventional (Utility)	21.7	35.9	42.0	9.3
Tandem (Heavy Lift)	25.4	45.4	52.0	14.2
Tilt Rotor (Cargo/Assault)	20.7	37.1	42.5	9.5

Table 5.4-3 Load Factor and Efficiency Assumptions

	Airframe	Landing Gear	Seat
Load Factor (g)	20*	5	14.5
Efficiency	0.8	0.8	0.9

* Acceleration Pulse (40g - max, 20g - average)

The results shown in Table 5.4-2 indicate that certain rotorcraft types have key crashworthiness design dimensions such that a sink rate of at least 42 fps is achievable for level impact on rigid surfaces. The sink rate capabilities of the Conventional types with attack and utility missions are comparable to known capabilities of AH-64 and UH-60. The sink rate capability for the Tandem type with cargo mission and the Tilt-Rotor type with the cargo/assault mission indicates these rotorcraft types would have higher crashworthiness potential then the current CH-47 and V-22 aircraft when high-energy absorbing landing gears and energy attenuating airframe structures are used.

Future rotorcraft designs may be slightly different from the types identified here(such as compound or co-axial types). Future developments are likely to focus on multiple roles for a single rotorcraft designs. Though the designs may bring about new types of rotorcraft, the same basic design considerations for crashworthiness should be followed. In areas of special concern, the specific design should be evaluated with current crashworthiness technologies, so the best crashworthy design is obtained.

Final conclusions of sink rate capabilities based on key design dimensions using energy balance equations and general models are TBD.

5.4.1 Elements of System Crashworthiness Design Overview

The overall objective of designing an aircraft and its systems for crashworthiness is to minimize occupant injuries and fatalities, enable emergency egress following a crash impact sequence, and minimizing aircraft impact damage. Accomplishing this requires the designer to use a systems approach, since like a chain, crashworthiness is only as good as its weakest link in the system. For example, if the landing gear absorbs energy as designed, the seating system remains attached and strokes properly, but the large overhead mass retention structure fails allowing penetration into the occupied volume, crash survivability will likely not be achieved. All of the systems must function together as needed to achieve the crashworthiness objective. Hence, the following system and process elements of crashworthiness should be addressed.

5.4.1.1 System Elements

5.4.1.1.1 Crash Energy Management

5.4.1.1.1.1 Energy Absorption

Energy absorption or energy attenuation is required to mitigate damage to occupants and high priority mission equipment packages. There are various methods to absorb (attenuate) the kinetic energy of a crash event. Overall system design is critical to providing adequate energy absorption.

5.4.1.1.1.2 Rotor System

Rotor systems can provide substantial energy attenuation prior to impact, depending on the event. Design considerations should be given to achieve good autorotation ability to reduce impact velocity. Autorotation is not always possible when crash events initiate too close to the terrain, or when there is insufficient forward velocity to initiate autorotation. To preclude fatal blade strike of personnel and equipment, the rotor blade must not intrude into occupied space.The main rotor hub and transmission should be attached securely enough that if the crash is survivable, there is no danger of the rotor hub or the transmission penetrating occupied space upon impact.

5.4.1.1.1.3 Vehicle Management System

Consideration should be given to active means of auto-flare to significantly reduce crash energy prior to impact. VMS systems that are able to detect imminent impact may be able to attenuate crash energy prior to (or possibly during) contact with the ground. Performance will be dependent on the crash scenario and the rotorcraft type and class.

5.4.1.1.2 Airframe Structures

The primary contribution of the airframe structure during a crash impact is to reduce the airframe accelerations through energy absorption and to maintain a survivable volume for the occupants. Energy absorption can be provided through crushing of the subfloor structure in a controlled manner. Additional energy absorption may also be provided by various energy attenuating mechanisms for the high mass items (transmission, engines, etc.), as well as through controlled deformation of the cabin frame structures. Tilt rotor type rotorcraft can also have energy absorption capability through controlled deformation of the wing structures (cf., § 5.4.1.1.3.3). Structural integrity is critical for occupant restraint, high-mass item retention/attenuation, maintaining load paths to energy absorbing features, and maintaining occupant space. Consideration should also be given to how the structure will be affected by impact surface variability.

5.4.1.1.2.1 Maintain Survivable Occupant Volume

The aircraft and its systems should maintain a protective, livable space for occupants and high priority mission equipment packages throughout the entire crash sequence. During the initial contact phase, survivable space may change dynamically as various components decelerate (e.g., seats stroke, structure buckles and collapses). Maintaining a survivable volume includes limiting the intensity of accelerations experienced by occupants and critical mission equipment packages to tolerable levels; properly restraining occupants, cargo, and equipment during the crash sequence; preventing injuries resulting from contact with barriers, projections, and loose equipment; limiting the threat to survival posed by fire, drowning, exposure, and entrapment; and enabling safe emergency egress following a crash impact.

5.4.1.1.2.2 Anti-Plow and Rollover Strength

5.4.1.1.3 Inertial Management

5.4.1.1.3.1 High Mass Management

High mass items that are above or behind occupied space must be managed during the crash sequence so that they do not penetrate the occupied space. These items generally include but are not limited to the main rotor transmission, engine(s), and large cargo. Management of these high mass items could mean retention, especially the helicopter main transmission and engine(s) so that it does not shift causing penetration or allow rotor blade penetration into the occupied space. However, management also includes controlled displacement through passive or active energy absorbers.

5.4.1.1.3.2 Cargo Management

Cargo is customarily not viewed as being high mass items requiring special retention. Instead, retention of cargo is based on load factors (see the appropriate structural design criteria report for the affected rotorcraft) derived from doctrinal use of the aircraft and a maximum gross weight of cargo. These load factors are not part of static crashworthy criteria. Thus, and from an airworthiness point of view, an aircraft may meet cargo load factor criteria, but not necessarily crash load factor criteria. Moreover, when the need arises to exceed the maximum cargo gross weight, a waiver is typically granted.(for this case, the aircraft does not meet cargo load factor criteria)

5.4.1.1.3.3 Kinetic Energy Shedding

A significant amount of kinetic energy may be eliminated from the aircraft system by judiciously designing controlled failure of sacrificial structural subsystems such as the tailboom on a helicopter or wings on a tiltrotor. For example, allowing the lower longerons of a tiltrotor wing to crumple or buckle at a sufficiently high load, but below the strength of the supporting fuselage bulkhead, prevents collapse of the fuselage (preserving a survivable space) as well as provides controlled downward and outward displacement of the massive nacelles and proprotors.

5.4.1.1.4 Static Crash Load Criteria

Static crash load criteria has been the traditional crashworthiness standard for more recent rotary wing designs. The static load criteria for the UH-60 and AH-64 aircraft designs is 20G FWD/AFT, 20 G DWN/ and 18 G LAT. For the Navy the criteria has been 20 G FWD/AFT, 20G DWN and 10 G LAT, which is the standard for the current V-22. These standards have proven to provide significantly more survivable crashes in the post-Vietnam era rotary wing aircraft. Because a crash is a dynamic event, static load criteria are not necessarily accurate nor provide an optimum solution. They are realatively easy to calculate and generally provide a conservative approach to crashworthiness when applied to an airframe or its subsystems.

5.4.1.1.5 Landing Gear Systems

The primary purpose of the landing gear system is to provide a structural interface between the airframe and the landing surface. The landing gear should be designed to minimize aircraft damage during hard landings and provide protection to the occupants by absorbing part of the system kinetic energy during crash impacts. The energy absorption capability of the landing gear is provided by plastic deformation of skid gear cross tubes or by the landing gear shock struts. Shock struts typically employ multi-stage oil-nitrogen systems to provide damping for ground resonance as well as energy absorption during crash impacts. Some shock strut designs also employ mechanical or elastomeric second stages to absorb the impact energy.

5.4.1.1.6 Occupant Seating and Restraint Systems

The purpose of seats and restraint systems during a crash impact is to securely restrain the occupants to minimize secondary impacts with the rotorcraft interior and also to reduce the spinal injuries experienced by the occupants through stroking of the seats. The seat stroke is typically accomplished by discrete energy absorbing devices that allow relative motion between the seat bucket and the seat frame attached to the airframe structure. Technology enhancements to seating systems are discussed in Section 5.4.4.2.2.

5.4.1.1.6.1 Human Tolerance Limits and Body Position

HIC, lumbar compression, pelvic acceleration

Femur breakage, tibia, fibula, humus, ulna, neck flexure, etc.

5.4.1.1.6.2 Mobile Occupant Restraint

The use of safe personnel restraint systems needs to become standard in rotorcraft requirements and design. While great strides have been made in pilot protection, the protection of people in the cargo areas has not kept pace. As a result, rear compartment occupants are injured or killed at nearly twice the rate of pilots. Furthermore, the use of the gunner's belt has been shown to result in severe injuries even though it does preserve lives. Gunner's belt design concentrates forces either around the waist or chest and the single lanyard provides no protection from flail trauma during rotorcraft mishaps. New restraint systems which properly immobilize occupants are essential. Torso suits and multipoint restraints are leading technological candidates. Each rotorcraft occupant should be entitled to an energy absorbing (stroking) seat and four or five point restraints. Occupants required to be out of crashworthy seating at speeds below ETL should have restraints which adequately protect them from flailing during mishaps and evenly distribute the inertial load during the impact.

5.4.1.1.6.3 Strike Hazard Mitigation/Delethalization

Some changes are cultural rather than engineering dependent. The Air Force and the Army do not require all passengers to wear helmets when aboard rotorcraft. Head injury is the leading cause of both injury and death aboard US military rotorcraft. The Navy has maintained an impeccable standard of head protection during helicopter operations and their injury data defines the improvements achievable by the other two service departments. Head protection should be worn by all occupants of rotorcraft. Another cultural issue encountered in military operations is the removing of restraints prior to landing or the initiation of a fast-rope deplanement. Some passengers unbuckle from their restraints a minute out from the landing zone or fast rope exercise. This occurs before the aircraft is either on the ground or stabilized in a hover. When mishaps occur during these operations, the outcomes for the unsecured occupants are predictably poor. Each service department needs to adhere to strict requirements to minimize the chance that someone is unsecured when a mishap occurs.

5.4.1.1.7 Prevent Post Crash Hazards

5.4.1.1.7.1 Crash Resistant Fuel System

The primary purpose of the crash resistant fuel systems is to minimize and delay the onset of post-crash fires. The systems include components such as break-away valves, frangible connectors, and tear and puncture resistant fuel tanks to minimize spill of fuel and lubricants during crash impacts (cf. Section 5.4.4.2.5).

5.4.1.1.8 Egress

Reference Sections 5.4.3.1.4 and 0

5.4.1.1.9 Communications

5.4.1.1.9.1 Emergency Locator Transmitter

Reference Section 0.

5.4.1.1.9.2 Crash Sensor and Data Recorder

5.4.1.1.9.3 Audio Instruction

5.4.1.1.9.4 Visual Cuing

5.4.1.1.10 Aircraft floatation

Reference Section 0.

5.4.1.2 Process Elements

5.4.1.2.1 Energy-centric Approach

5.4.1.2.2 Analysis Validation

Reference Section 5.4.5.

5.4.1.2.3 Test Verification

Reference Section 5.4.5.

5.4.1.2.4 System and Subsystem Modeling and Simulation

5.4.1.2.5 System Engineering Process- Requirements to capability

5.4.1.2.6 Egress

Reference Sections 5.4.3.1.4 and 0

5.4.1.2.7 Crashworthiness as an Element of Overall System Design

5.4.2 Mission Considerations Affecting Crashworthiness

5.4.2.1 Operational Environment

Operational environment plays a role in the design of an aircraft system for crashworthiness. An aircraft may have a higher probability of crashing in the environment it most often operates. Environment includes the terrain, climate, and operating conditions that an aircraft is in when a crash occurs.

5.4.2.1.1 Effects of Terrain

Aircraft will conduct operations over all types of terrain, over a large range of temperatures and climates. Various terrains can be categorized into five types: Rural, Urban, Mountainous, Forest, and Water. Designing for crashworthiness over these terrains will present various challenges as described below. While there are locations that have multiple aspects of these terrains combined, a crashworthiness criteria that can address all terrains will be more beneficial to the user and improve the probability of occupant survivability.

Rural terrain includes, flat, deforested areas with minimal foliage and few, if any obstructions. Operating in this environment is less of a risk than the other terrains described below. Surfaces can vary significantly: Soft soil, hard soil, rock, sand, ice, snow.

Urban terrain include cities, and man-made structures and surfaces. Operating in this terrain limits an aircraft's speed mobility as missions may require direct engagement in this environment. Aircraft may be required to hover, circle at low altitude, or cruise at either high or low altitude above this terrain. During a crash event, an aircraft has a high probability to horizontally impact vertical man-made structures (wires, buildings, towers). This primary impact will then be followed by a secondary impact with the ground. The ground can be un-even and/or prepared, hard surfaces.

Mountainous terrain can be at high-density altitude with uneven and sloped surfaces. Although at a high-density altitude, an aircraft may be flying relatively close to the ground (i.e. low AGL). Operating in this environment can limit an aircrafts power available during a crash event. Horizontal impact velocity into ground may be significant. Surfaces are most likely natural, can be uneven, unprepared, and sloped.

Forest terrain includes jungles or areas with foliage that inhibit direct impact with the ground. Operating in a forest terrain presents difficulty in determining exact altitude above ground level. In a crash event, horizontal and vertical impact with trees presents difficulty to the pilot's ability to crash in a controlled manner. There is a risk of impaling of branches into the cockpit or cabin. After a primary impact with trees, and loss of rotor lift, secondary impact with the ground could be at a higher velocity and at any angle, as compared to an impact on a flat, deforested terrain.

Traditional rotorcraft crash analysis has typically been driven by requirements for impact with a rigid flat surface. For full spectrum crash criteria, two idealized surfaces, water and soft soil, have been added. Army, Navy, and civil studies have characterized impact surfaces differently, but these surface characteristics could be categorized as rigid, soft soil, and water. The aforementioned terrains all have the possibility of the rotorcraft impacting soil or water (in some form). With respect to soil, the type and composition of the soil can vary greatly and could affect energy attenuation significantly during a crash event.

In order to ensure a robust crashworthy airframe design, full spectrum crashworthiness requires compliance with impact scenarios onto three idealized surfaces; rigid, water, and soil. If dynamic simulation is to be used to address the soft soil impact requirements, simulation models will most likely need to represent soils of various compositions. Soil can be described based on its percentage makeup of three basic constituants: Clay, Sand or Silt. The United States Department of Agriculture soil texture triangle (Figure 5.4.2.1.1-1) can be used to describe soil compositions.

This work was conducted under the Full Spectrum Crashworthiness Program for AATD.

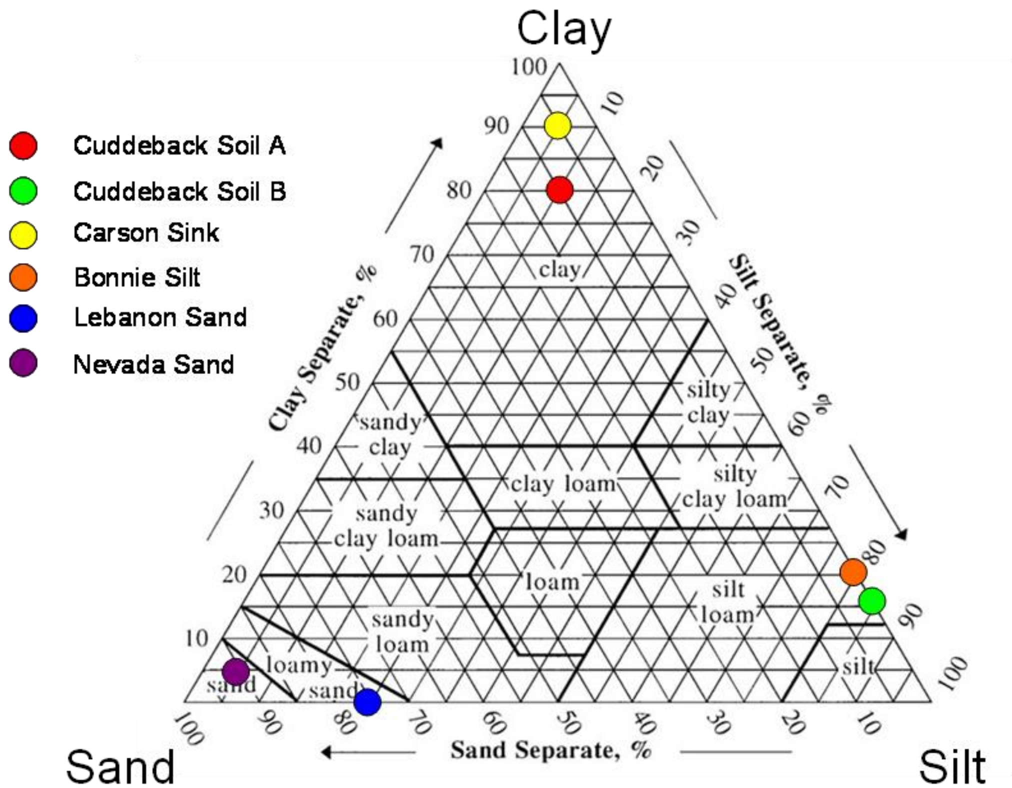


Figure 5.4.2.1.1-1 USDA Soil Texture Triangle

Water terrain includes oceans, lakes, rivers, and marshland areas. Operating in this environment is dependent on the sea-state (if applicable), and type of mission. Navy operations include transportation of supplies between two ships and require low, slow flight with payload. Army operations include transportation of personnel or supplies from sea-bases to shore at cruise speeds at either high or low altitude. The sea-state that a crash occurs in can change the impact velocity and the angle of impact. Sea states range from 1 (calm, no waves) to 9 (phenomenal', over 14m wave swells). The probability of flying in a sea state is dependent on its probability of occurrence, and likelihood that a mission would necessitate flight in that state. Based on the annual probability of sea states (Figure 5.4.2.1.1-2) a 95-percentile sea state of 6.6 could be a conservative representation of likely occurring sea states.

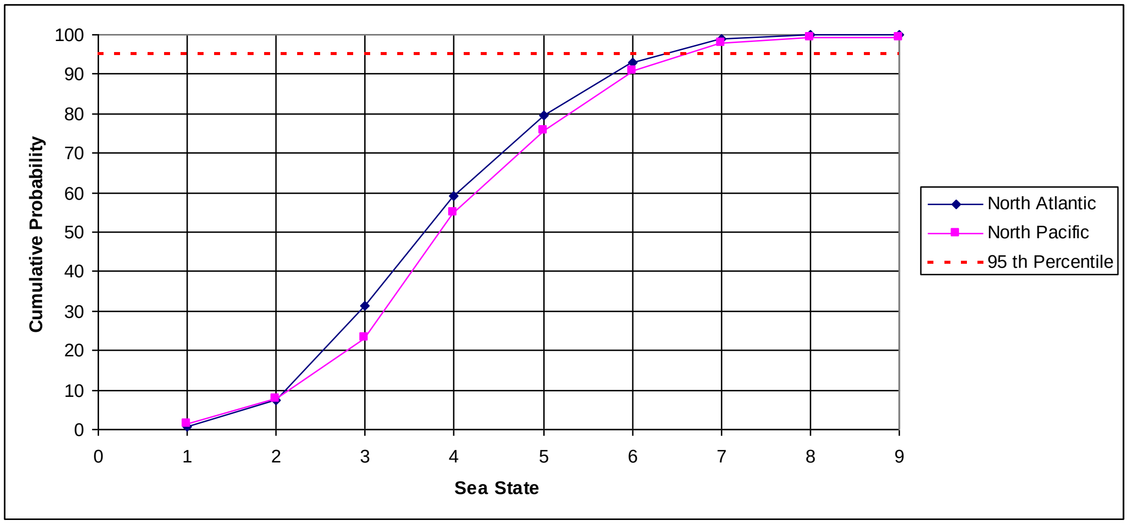


Figure 5.4.2.1.1-2 North Atlantic and North Pacific Cumulative Probability of Sea State

Water terrain also adds a unique crashworthiness aspect in that safe and fast egress is critical for occupant survivability. A person's ability to remain conscious is a critical component of egress. Impacting water (liquid) also presents challenges for crash systems that were designed to impact the other types of terrain (solid). Fuselage impingement on the water could cause the aircraft skin to burst. Various crash survivability systems such as landing gear may not operate optimally in a water environment.

5.4.2.1.2 Climate

Climate includes ambient temperature, precipitation, wind velocity, visibility, and sea states. In a high/hot climate, an aircraft's autorotation capability is limited. In extreme cold weather climates, energy attenuation systems may operate differently unless care is taken in the design. In poor visibility climates, impact with terrain could occur at higher velocity than otherwise expected due to the reduced reaction time of the pilot. Wind gusts and high sea states could increase the possibility of roll over or initiate impact with terrain. The extent that a system can mitigate variations in climate prior to impact can greatly affect the crashworthiness of the system.

5.4.2.1.3 Operating Conditions

How an aircraft is flown could indicate how it will likely crash. Variations in altitude and airspeed can affect how an aircraft will crash into various terrains, and dictate reaction time requirements for active crash protection systems. The mission and flight regime that an aircraft is in when a crash event starts, could affect the performance of the crash survivability design.

5.4.2.2 Rotor Type Considerations

5.4.2.3 Size Class Considerations

5.4.2.4 Mission Considerations

5.4.2.4.1 Tactical vs. Non-tactical

5.4.2.4.2 Carrying Personnel vs. Cargo

5.4.2.4.3 Sea-based vs. Land-based

5.4.2.4.4 Long endurance vs. Short endurance

5.4.2.4.5 Medical Evacuation

5.4.2.5 Effects of Operational Variability

5.4.2.5.1 Impact Surface

5.4.2.5.2 Operating Weight

5.4.2.5.2.1 Designing for Weight and Center of Gravity Variability

For most military aircraft, the term "structural design gross weight" is synonymous with the "design gross weight."

For a rotorcraft, that is compliant with modern crash criteria defined at structural design gross weight, it would be expected that the crash capability would decrease at higher operational gross weights. Historically, structural design gross weight was tied to an operational mission. However, it is conceivable that a structural design gross weight could lose operational significance as the aircraft matures. To maintain crash performance at increased operational gross weights, the manufacturer most likely would need to intercede and add more energy attenuation capability to the derivative aircraft. In order to accommodate this change, full spectrum crash criteria can be tailored such that the design weight for crash analysis could become a percentage of the maximum take off weight, and this would ensure crash capability is maintained as the aircraft grows.

5.4.3 Design for Post-crash Survival

The objective for this section is to provide the scope and background that enables safe escape from the aircraft and survival for crew and passengers, after a survivable impact.

5.4.3.1 Post-Crash Survival

The survival of aircraft occupants following a crash or ground emergency is often dependant upon the ability of occupants to rapidly evacuate the aircraft before the local environmental conditions (i.e. post-crash fire, toxic gasses, water immersion, etc.) cause injury. Therefore, the aircraft must include an emergency egress system that enables all occupants to perform their own escape before being overcome by threatening post-crash environmental conditions. Additionally, systems must be provided that eliminate, mitigate, or protect against post-crash environmental hazards so occupants are not incapacitated before completing their safe escape. This can include integration of crash resistant fuel systems, fire suppression systems, aircraft floatation systems, personal breathing devices, and an overall aircraft safing system that automatically or manually deactivates aircraft systems that pose potential dangers during egress.

5.4.3.1.1 Egress Time

The top-level parameter most often used to specify overall performance of an emergency egress system is the total time required to evacuate the aircraft under post-crash conditions. For a specific aircraft application, the actual time limit for emergency evacuation should be determined by an analysis of specific emergency egress needs and threats. The analysis should take into consideration factors such as anticipated post-impact environmental hazards (e.g. fire, toxic gasses, submersion, darkness) and their associated time dependencies and life-threat relationships. An example showing factors to be included in a time-line analysis for underwater egress from a helicopter is shown in Figure 5.4.3.1.1-1.

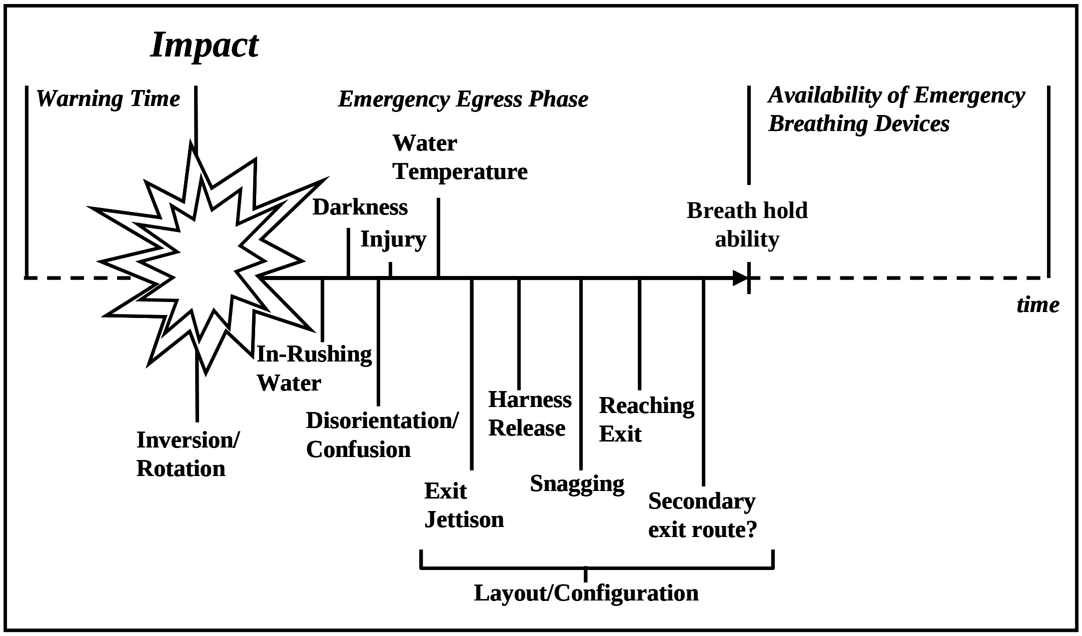


Figure 5.4.3.1.1-1 Example Emergency Egress Timeline for a Water Crash

Key design parameters include the ratio of the number of exits to the number of occupants, exit sizes and geometry, exit release mechanisms, distance to exits, and a breakdown of the tasks required by occupants to use the emergency egress system. The functions of an emergency egress system are also affected by the performance of other aircraft systems and equipment. For example, aircraft deformation can jam emergency exits, and intrusion of aircraft structure can block escape paths. Because of these and other interrelationships, the emergency egress system must be designed using a systems engineering approach taking into account the various aircraft elements identified as having a functional impact on emergency egress. The allocation of specific systems and equipment to facilitate emergency egress should be based upon the results of an emergency egress trade study that is part of the overall aircraft design trade study.

5.4.3.1.2 Aircraft Safing

During a crash some rotorcraft systems required for flight can suddenly become major post-crash hazards to aircraft occupants. Examples include systems such as electrical systems (generators and batteries) which can become fire ignition sources, and fuel pumps continuing to operate which can increase the risk of dispersed fuel. Engines continuing to operate with rotating blades can also introduce hazards to evacuating occupants. Due to injury and their own survival needs, pilots may not always be able to perform all necessary procedures to shut down such aircraft systems that might still be in an active state after a survivable mishap. For this reason, to facilitate safe evacuation consideration should be given to including a crash activated safing system that automatically places applicable aircraft systems in the appropriate post-crash mode.

5.4.3.1.3 Emergency Exits

A sufficient number of exits must be provided in order for all occupants to quickly evacuate the aircraft during a ground emergency or after a survivable crash. The number of exits, their sizes, geometry, location, and ease of opening has a direct affect on an occupant’s ability to egress rapidly in an emergency before becoming overcome by post-crash environmental conditions such as fire, toxic fumes, and submersion.

Helicopters with relatively wide fuselages pose egress difficulties in situations where the helicopter comes to rest on its side, because in that orientation the ground blocks the exits on one side (now down), and the exits on the other side (now up) can be out of reach. With these aircraft configurations it is extremely valuable to have exits in the aircraft’s ceiling and/or floor when possible.

Pyrotechnically opened exits have been found to have advantages of being able to reliably open even after sustaining impact deformation that can jam conventional mechanical release mechanisms. Also, pyrotechnically opened exits have been found to have weight advantages, and were for that reason selected for the especially weight sensitive V-22 tilt rotor. In addition to using pyrotechnics to open conventional hatches, line charges can be used to cut open exits in other areas of aircraft structure.

5.4.3.1.4 Emergency Egress Routes

Specific definition of the required escape route configuration depends on the aircraft type, its seating layout with respect to emergency exits, and on the anticipated post-crash conditions of the aircraft. Emergency exits which are located on the aircraft sides may not be accessible in cases where an rotorcraft has rolled onto its side, which is common for rotorcraft. In these cases, special hand-holds may be required to provide access to the exits. Alternately, or additionally, emergency exits can be installed in the aircraft ceiling and/or floor to provide better access.

Design of these egress routes that will be used for underwater escape must take into account that fact that the occupants will be essentially swimming, pushing, and pulling themselves underwater to their exits. It is vital that hand-holds be interspersed throughout the entire escape path so that occupants can maintain a grip on aircraft structure at all times; from the time they depart their seat until they are outside an aircraft emergency exit. The hand-holds serve the dual purpose of providing fixed points from which occupants can pull themselves through the aircraft interior, and providing critically needed reference points to maintain spatial orientation. In some cases the hand-holds can be continuous guide bars spanning the entire length of the cabin. To assist in darkness, the guide bars can be either self-illuminating, or lighted from an external source. Guide bars can also have tactile indicators to identify when an exit has been reached. When a series of single point hand-holds are used, they should also be illuminated with emergency lighting.

Because of the human factors associated with underwater escape, the military uses underwater training devices to provide military aircrew and troops with emergency egress practice. These training devices are modular and configured for specific aircraft types to train crew to egress from the aircraft type they will be flying. For this reason, aircraft development programs need to coordinate with the military training commands so any unique training requirements are taken into consideration. For example, if crew served weapons are to be mounted in escape windows or hatches, means of jettisoning the weapon need to be included in the aircraft design, and added to the training systems.

5.4.3.1.5 Emergency Egress Lighting

Emergency egress lighting is needed to enable aircraft occupants to quickly locate emergency egress paths and exits that could otherwise be obscured by smoke or underwater conditions, particularly at night. The emergency egress lighting system should be automatically activated as part of the aircraft's integrated crash sensing system. Emergency Egress lighting should also operate when other electrical systems are deactivated due to fire prevention measures.

5.4.3.1.6 Localized Entrapment Prevention

Military mishap experience have revealed many ways that impact survivors have been entrapped within an aircraft and then killed by post-crash environmental conditions such as fire, toxic gasses, and submersion. An effective emergency egress system must be developed with an understanding of these real world hazards and include design mitigation strategies. Entrapment is often not caused by a single obstacle to egress, but by the combined affect of several partial restrictions including airframe deformation resulting in partial loss of occupiable space, jammed exits, shifting of internal cargo and mission equipment that blocks exits, and protrusions in the aircraft interior that cause snag hazards.

5.4.3.1.7 Fire Prevention / Suppression

Before the introduction of crash resistant fuel systems, post-crash fire was the leading cause of death in otherwise survivable crashes. Post-crash fires were found to prevent successful emergency egress by causing both fatal thermal injuries and fatal breathing related injuries due to toxic fumes. Crash resistant fuel systems greatly facilitate enable safe escape by preventing post-crash fires through preventing the release of fuel during and after the crash. These systems use design features including puncture resistant fuel bladders and self-sealing breakaway fuel lines. Successful implementation of crash resistant fuel systems has virtually eliminated thermal injuries in survivable rotorcraft crashes and should be an integral part of any future rotorcraft. Additional background about these systems can be found in MIL-STD-1290 and the Aircraft Crash Survival Design Guide (USAAVSCOM TR 89-D-22E) Volume V – Aircraft Postcrash Survival. Fire suppression systems can also be included in rotorcraft system designs to further reduce the risk of fire related injury. These systems can be positioned in the engine compartment in areas susceptible to fire initiation upon impact. They should be automatically activated as part of the aircraft's integrated crash sensing system, either due to impact acceleration (fire preventive), or when a temperature threshold is exceeded (fire reactive). When activated, fire retardant materials are either dispersed into the compartment, or inert gasses are suddenly blown into the compartment to extinguish the fire.

5.4.3.1.8 Aircraft Flotation

When conventional rotorcraft (non-tilt rotor) ditch or crash in water without aircraft floatation systems they typically invert almost immediately and are often below the surface in less than 15 seconds. This response in water is due to the high center of gravity associated with conventional rotorcraft designs and large aircraft openings that often remain open in-flight due to combat mission requirements. Rapid water entry can also be caused by structural damage incurred during water impact. Examples of high mass items contributing to the high center of gravity in conventional rotorcraft include engines and gear boxes located above the fuselage. Examples of large openings that often remain open in flight include cargo ramps, troop access doors, and gunner windows. Because of the post-crash response with these configurations in water, rotorcraft occupants can become disoriented during inversion, overcome by in-rushing water, and susceptible to drowning. Tilt rotor aircraft can have a different stability problem of tending to pitch nose down or nose up about the axis of the wing. Regardless of type, rotarywing aircraft have unique and significant floatation issues when crashing into water.

Aircraft floatation, whether inherent or supplemental, can provide the additional time and stability needed for occupants to successfully egress the aircraft before submersion. Supplemental floatation systems, generally in the form of deployable floatation bags, are used on some rotorcraft to both stabilize the aircraft in roll and pitch, and to delay submersion for evacuation. Automatic operation increases the probability of the system actually being used in a crash since pilots, due to their own injuries, may not be able to manually activate the system after crashing. Activation should be initiated by the aircraft's integrated crash sensing system, including sensors that detect contact with water. Deployable flotation bags are required on civil rotorcraft that fly beyond a threshold distance from coastlines.

As an alternative or supplement to deployable flotation bags, inherent floatation can also be provided by insuring the rotorcraft has sufficient built-in buoyancy to retard sinking and provide stability. This generally requires that pre-determined compartments within the aircraft structure are designed remain structurally air tight after a ditching or water crash.

5.4.3.1.9 Life Rafts & Personal Flotation

For rotorcraft operating overwater, provisions must be included in the rotorcraft design for stowage and deployment of life rafts for the maximum number of aircraft occupants. The life raft size, weight, and its stowage provision must take into account the amount of time available for deploying the life raft considering the predicted rotorcraft post crash orientation in the water and it's sink rate. In some cases it may be necessary or preferable to have automatically deployable life rafts installed in external sponsons or other aircraft compartments near the outer surface. If automatically deployed, it should be initiated by the aircraft's integrated crash sensing system. Manual deployment of life rafts can significantly reduce their effectiveness. For military aircraft personal life preservers are normally included as part of the body borne equipment ensemble, but if not, provisions should also be provided in the aircraft for stowage of and quick access to personal life preservers for all occupants.

5.4.3.1.10 Supplemental Breathing Air

The U.S Navy has developed small underwater breathing devices provided to aircrew and troops flying overwater in rotorcraft. These compressed air sources can attach to their survival vests or seats, and generally provide several minutes of emergency breathing air. This supplemental breathing provides additional time for occupants to overcome egress problems they may encounter when performing the difficult task of egressing a rapidly sinking inverted rotorcraft. These systems, referred to as Helicopter Breathing Air Device (HBAD) have been very successful in increasing survival rates in Naval mishaps at sea.

Breathing air devices have also been found to facilitate egress in ground mishaps where occupants would otherwise be overcome by smoke and toxic fumes. These devices are provided in the form of smoke hoods made from transparent heat resistant materials that enable users to both breathe and open their eyes in smoke and toxic fumes. These devices are sometimes installed in seating systems within reach of seat occupants. Their most common application is for aircrew in fixed wing transport aircraft, but they are now being used in rotorcraft applications as well.

5.4.3.1.11 Search And Rescue (SAR) Aids

After successfully egressing an aircraft, the ultimate goal of occupant survival can then depend on how quickly the surviving occupants are rescued, taking into consideration any life threatening injuries sustained during the crash requiring medical attention, and outside environmental conditions. In military operations there is the additional factor of being rescued before being captured by hostile forces.

Rapid rescue can be facilitated by including an Emergency Locator Transmitter (ELT) that is automatically activated through the aircraft's integrated crash sensing system. However, the system must be designed to ensure that hostile forces cannot detect aircraft post-crash transmissions. Aircraft should also be equipped with other signaling equipment such as radios, flares and smoke generators.

5.4.3.2 Drowning Prevention

Water impacts have a greater deceleration distance that allows for lower G forces on impact and theoretically fewer and less severe human injury. The nature of existing DoD rotary wing platforms are such that when the helicopter impacts water it will almost universally become inverted and sink. This pattern contributes to an increased frequency of drowning by causing an otherwise survivable mishap to be further complicated by reducing the occupiable space during the impact phase and adding disorientation to the egress phase. Thus, while water impacts could induce less damage to the occupants, if drowning isn't prevented the effective crashworthiness is not improved. Ensureing safe egress and drowning prevention can greatly increase occupant survivability in a water impact.

An analysis of all the helicopter mishap drownings that occurred in the US Department of the Navy (DoN) from the period of 1985 – 2005 found that 23 of the 28 cases were before 1995. Furthermore, 105 additional fatalities that occurred during the same period were categorized as "lost at sea." The cause of death in these cases may have been drowning, trauma, or exposure. Prevention of over-water deaths must therefore also include consideration of these factors that are unique to over-water mishaps. The changes made by the DoN in the mid 1990's created a seven-fold reduction in over-water fatality risk. Forty percent of DoN helicopter fatalities in the first decade were a result of drowning or becoming lost at sea. The DoN reduced the proportion of the fatalities caused by water from 1995 - 2005 to only ten percent.

Multiple policies caused an improvement in water impacts in the late 1990's. Perhaps the most successful of these policies is the required underwater egress training (UET), also known as "dunker training." The UET simulates the helicopter water mishap scenario in a mock helicopter flight deck and crew compartment that is lowered into the water and inverted. Dunker training skills focus on techniques that reduce disorientation and prevent additional trauma during egress. Trained crew members become proficient at egress from an upside down restrained position in the dark.

Small compressed air bottles t are added to the survival vest for helicopter aircrew flying over water. This device includes a regulator and mouth piece similar to typical recreational SCUBA gear. The usual volume is sufficient to provide a few breaths of air depending upon water depth and respiratory rate. Compressed air bottles have provided the additional time required for multiple cases of safe water environment egress. The combined experience of UET training and the availability ofcompressed air bottles provides an additional unmeasured benefit of confidence that is essential in an underwater helicopter mishap situation.

5.4.3.3 Integration Design for Injured Crew

Ease of use, simplicity of components for egress, fail safe equipment that still provides functionality with damage, dual use equipment (troop seat used as a tent, seat cushion is your flotation device, cabin soundproofing-blanket, cargo doors-shelter).

5.4.4 Applicable Technologies

5.4.4.1 Identification of Crashworthy Design Features

5.4.4.2 Technologies Organized by Subsystem

5.4.4.2.1 Airframe Structures

The primary purpose of the airframe structure during a crash impact is to reduce the airframe accelerations through energy absorption and to maintain a survivable volume for the occupants. Energy absorption can be provided through crushing of the subfloor structure in a controlled manner. Additional energy absorption may also be provided by various energy absorbing mechanisms for the high mass items (engines, transmission, etc) as well as controlled deformation of the cabin frame structures. Tilt rotor configurations can also have energy absorption capability through controlled deformation of the wing structuresas well.

5.4.4.2.1.1 Energy Absorbing Structure

5.4.4.2.1.1.1 Pressure resistant skins

5.4.4.2.1.1.2 Alternate Load Path Structures (depending on impact conditions)

5.4.4.2.1.2 Major Mass Retention

5.4.4.2.1.3 Structural Integrity / Maintain Livable Space

5.4.4.2.1.4 Anti-plowing

5.4.4.2.2 Seats and Restraint Systems

The purpose of seats and restraint systems during a crash impact is to securely restrain the occupants to minimize secondary impacts with the rotorcraft interior and also to reduce the spinal injuries experienced by the occupants through stroking of the seats. The seat stroke is typically accomplished by discrete energy absorbing devices that allow relative motion between the seat bucket and the seat frame attached to the airframe structure. The current seat energy absorber technology includes fixed load energy absorbers that are designed for 50th percentile occupant weight as well as variable load energy absorbers that can be adjusted for the occupant weight.

Lap belt restraints do not offer sufficient protection in an aircraft crash event. Flailing of the arms and upper torso can cause life threatening secondary impacts. Modern restraint system technologies include the 4- and 5-point type restraint systems with low elongation webbing and dual mode locking inertia reels. There are also supplemental restraint system technologies such as Cockpit Airbag Systems (CABS) and belt-retractors to position the occupants correctly prior to the crash impact and to reduce flailing during the crash impact.

5.4.4.2.2.1 The full spectrum crashworthiness criteria are at the system level and do not include detailed seat and restraint system design requirements. The requirements include not-to-exceed occupant injury threshold levels. These requirements can be met by system level design integration through a combination of seats and other crashworthy subsystems. Adaptive Energy Absorbers

5.4.4.2.2.2 Active Constraints / Prepositioning

5.4.4.2.3 Landing Gear

The primary purpose of the landing gears is to minimize the aircraft damage during hard landings and provide protection to the occupants by absorbing part of the system kinetic energy during crash impacts. The energy absorption capability of the landing gears is provided by the landing gear shock struts. The shock struts typically employ multi-stage oil-nitrogen systems to provide damping for ground resonance as well as energy absorption during crash impacts. Some shock strut designs also employ mechanical or elastomeric second stages to absorb the impact energy. If a rotorcraft impacts onto soft soil at crash sink speeds, the landing gear performance is thought to be compromised. However, the deformation of the impact surface does attenuate some of the crash impact energy (A similar analogy is thought to apply for water impacts as well.). LS-DYNA modeling parameters have been derived for a variety of soil types and simulations could be capable of determining the effectiveness of landing gear impacts on soft soil and the quantification of crash energy by the soil deformation.

Current landing gear technology is based on fixed hydraulic orifice and metering pin technologies. One drawback of this technology is that the shock strut loads can exceed design strength allowables at high impact velocities. More advanced landing gear shock struts using pressure sensitive orifice technology to solve this problem have successfully been developed and are beginning to transition into production. The effectiveness of the landing gears also to a large extent depend on the impact surface. The landing gears are not effective during crash impacts on water and, to some extent, on soft soil.

Full spectrum crashworthiness criteria is at the system level and does not include detailed landing gear design requirements. The FSC requirements have a minimum vertical impact capability. The landing gear design will also need to be adaptive to the changes in aircraft gross weight and center of gravity.

Research and development activities are focused on shock strut improvements and others are focused on improving structural efficiency of the landing gear structures. The shock strut improvements include optimizing stroking loads through modulation of orifice size as well as viscosity of the hydraulic fluid. Landing gear structural efficiency improvements have been focused on application of advanced composite materials to landing gear components such as trailing arms and drag braces.

5.4.4.2.4 Externally Deployable Energy Absorbers

The purpose of the externally deployable energy absorbers is to supplement the energy absorbing capability of the rotorcraft system. These systems can be deployed when needed to minimize the aircraft damage by supplementing the landing gears during hard landings as well as to minimize or eliminate occupant injuries by supplementing both landing gears and energy absorbing airframe structures. It is anticipated that the externally deployable energy absorbers will be part of rotorcraft crash activation systems with capabilities to sense an impending crash event and control the appropriate crashworthy subsystems.

Externally deployable energy absorbers will play an important role in meeting FSC requirements. They can provide technology solutions for multi-terrain impacts (water and soft soil) where some of the crashworthy subsystems such as landing gears would not be effective. They also provide a capability to increase the energy absorption capability as the aircraft gross weight increases and also compensate for center of gravity shifts by selective deployment during crash impact events.

5.4.4.2.5 Crash Resistant Fuel Systems

The primary purpose of the crashworthy fuel systems is to minimize and delay the onset of post-crash fires. The systems include components such as break-away valves, frangible connectors, and tear and puncture resistant fuel tanks to minimize spill of fuel and lubricants during crash impacts.

FSC requirements are expected to be at the system level and will not include detailed crashworthy fuel system requirements. The crashworthiness of the fuel system is included in the CI using an approach similar to ADS-11B, with a scoring based on the fuel system meeting current requirements for fuel systems. Depending on where the fuel tanks are located, the fuel system can also influence the design of the surrounding airframe structure. The surrounding structure needs to be designed to withstand the hydrodynamic pressures from the fuel tanks during the crash impact.

5.4.4.2.6 System Level Technologies

5.4.4.2.6.1 Integrated Active Crash Protection System

5.4.4.2.6.1.1 Sensors

Operations in DVE below ETL require special equipment as the flight visibility can quickly drop to zero and leave the crew unable to successfully cope with the DVE. At present, several options are available to deal with the DVE threat. Sensor technology may be an option for this challenge. The first candidate is 'see through' technology which uses high power millimeter wave radar to view objects through obscuring clouds of dirt or snow and presents the view to the pilot. Another sensor technology candidate is 'see and remember' technology which uses LIDAR to detect obstructions (before the DVE develops) and create a virtual image that is subsequently made available to the pilot during the landing. Flight control law technology is another potential avenue for dealing with DVE. An automatic landing system which could take a helicopter safely to the ground without pilot input would permit routine DVE landings. Alternatively, an 'auto hover' capability, instantaneously available to each pilot could prevent a host of bad DVE outcomes and permit safe landings in conditions with no visibility. These automatic maneuvers could also mitigate the severity of a crash event by maximizing energy dissipation prior to impact with the ground.

5.4.4.2.6.1.2 Electronic Controllers

5.4.4.2.6.1.3 Algorithms

5.4.4.2.7 Rotor System

5.4.4.2.7.1 Break-away Blades

5.4.4.2.7.2 Active Rotors

5.4.5 Design Validation

The Department of Defense uses Technology Readiness Levels (TRLs) and Manufacturing Readiness Levels (MRLs) to quantify the maturity of technology and manufacturing capability. A similar approach to assessment of analytical models is proposed with an Analytical Tool Readiness Level (ATRL). This assessment is based on an analytical tool's correlation to test data as well as predict untested scenarios.

Depending on the maturity of a design, and the robustness of the modeling tool, various ATRL levels could be necessary to provide validation. Configuration trades can be made with lower ATRL tools, while detailed analysis of specific components would require robust modeling tools to account for variations in crash scenarios (e.g. impact surface, roll, pitch yaw, etc). Until ATRL 7 is reached, M&S should be used in a building block approach with component level correlation. A building block approach will help establish confidence between test and simulation at component level (e.g., statistical Hypothesis Testing) and allow for of calibrated (correlated) components to system level assessment.

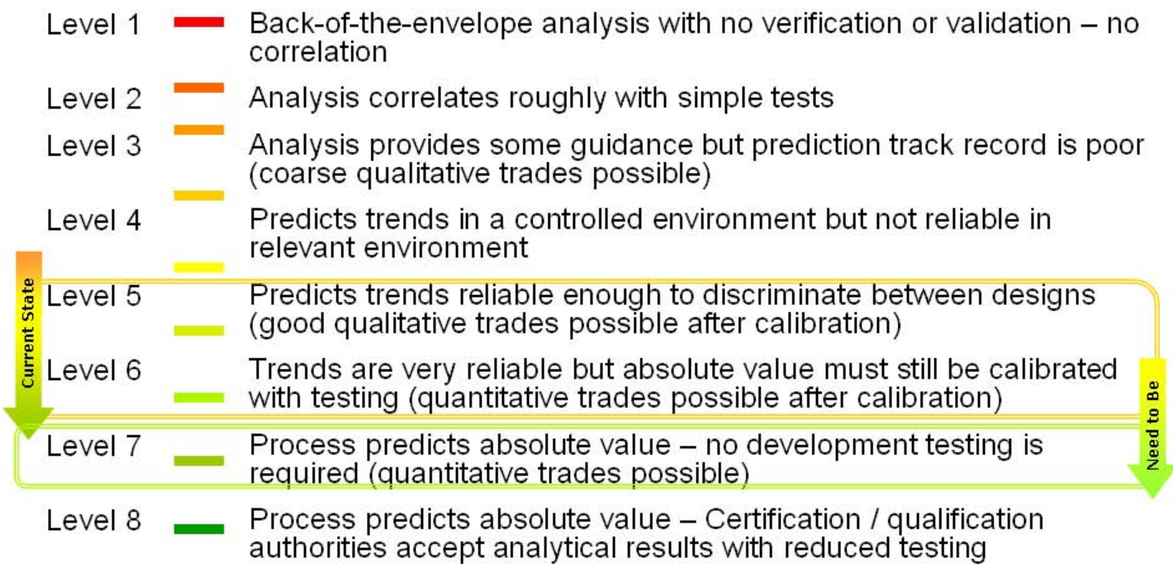


Figure 5.4.5-1 Proposed ATRL Assessment [2]

5.4.5.1 Modeling,Analysis and Testing

5.4.5.1.1 Analysis and Testing

5.4.5.1.2 Occupant Modeling

5.4.5.1.2.1 Validation

5.4.5.1.2.2 Injury Assessment

5.4.5.1.3 System Level Validation Plan

5.4.5.1.4 Risk Identification and Mitigation

5.4.5.1.4.1 Risk Assessment

5.4.5.1.5 Pre-Full Scale Test Model Validation

5.4.5.1.6 Validation Standards

5.4.5.1.6.1 NASA STD 7009

5.4.5.1.6.2 ASME V&V 10-2006

5.4.5.1.7 Building Block Approach to Model Validation

5.4.5.1.8 Model Interface with Total System Performance

5.4.5.1.8.1 System Interface

5.4.5.1.8.2 System Modeling

5.4.5.1.8.3 Structural Modeling

5.4.5.1.8.3.1 Sub-System Modeling

5.5 Crashworthiness Index

5.5.1 Probabilistic Approach to Crash Criteria

Traditionally, crash criteria have been prescriptive. The severity of crash impact conditions have been based on pre-existing crash statistics along with engineering judgment and feasibility of designing to certain conditions. There are many instances where aircraft have not been fully compliant with the requirements of crash criteria due to many reasons, including conflicting design requirements and excessive weight and cost penalties.

An alternative approach may be used to better quantify an aircraft's crash protection. Probabilistic crash criteria may be able to provide crash protection based upon the expected operational environment in which the aircraft will operating. In this approach, anticipated usage might emphasize certain aspects of crash protection. Operational usage estimates would be used to determine time spent over different terrain, at certain gross weights or in various flight regimes. Weighting factors would be used to express the importance (to the customer) of a particular crash attribute.

The crash index will describe how a composite rating can be used to measure how well a design meets crashworthiness criteria, enable trading between design features to minimize weight and cost, and provide a tool for increased communications between designers, Program Managers, Integrated Product Teams, and customers.

The crashworthiness index is a composite rating that is a summation of several factors/attributes. Each factor/attribute will be made of two terms. The first is a probability defined by various cumulative occurrence curves derived by kinematic mishap analysis. The second term is a customer weighting based on predicted usage (mission).

For example, the calculation of the crashworthiness index is envisioned to follow the general formula:

$$Rating = \sum_{i=1}^{n} \left(f_i * p_i \right)$$

The variable, f_i, represents a weighting factor that is set by the customer to reflect the importance of a particular crash attribute represented by the index, i. For example, a Navy or Coast Guard customer may want to emphasize water-impact sink speed capability more than an Army customer might. The variable, p_i, represents a probability factor that is derived from mishap statistics. Considering the water-impact example, a full value of p_i might be assigned if the new design was capable of the 95th percentile vertical crash impact sink speed derived from water mishap statistics. If the design was capable of a lower percentile impact sink speed, the value of p_i would be less.

It is envisioned that the number of crash attributes would be less than 50. A partial list of the attributes might include pitch angle capability for a vertical crash impact, roll angle capability for a vertical impact, sink speed capability for a rigid surface vertical impact, sink speed capability for a vertical soft soil impact, sink speed capability for a vertical water impact, velocity for a lateral crash impact, and velocity for a longitudinal crash impact. During the next quarter, the list of attributes will be further defined and a method to derive the *f* and *p* factors will be proposed.

5.5.2 Model Validation

This section will describe the scope and process for Modeling and Simulation (M&S) centric validation of the crashworthy systems and subsystems.

The crashworthy design validation M&S centric approach begins with a system level validation plan and the development of a full scale, full system model. Perform a system level risk assessment to identify areas of concerns/risks in the subsystem and component models. In concert, also identify threshold and objective confidence levels in the model, once the accuracy of the model is established, mature the model through impact testing of components and if necessary subsystems.

5.5.3 Crashworthiness Index

A scorecard that will aide/supplement the M&S validation process. The validation plan, executed thru a building block validation approach will interact with the elements of the crashworthy subsystem and system design to ultimately achieve an optional crashworthy index score.

6. Requirements

6.1 General Requirements

The overall system CI will be a function of the impact conditions met in Section 5.4, the level of occupant protection achieved, attenuation of cargo and high mass item kinetic energy, post crash survival considerations, and an assessment of off-design conditions:

$$CI^{SYS} = CI^{DI} + CI^{OP} + CI^{HMI} + CI^{PCS} + CI^{OD}$$

Where:

CI^{DI} = Impact condition performance
CI^{OP} = Occupant protection performance
CI^{HMI} = retention / mitigation of High Mass Items (including cargo) performance
CI^{PCS} = Post Crash Survival Performance
CI^{OD} = Off-Design performance

Crash requirements outlined in this section can also be weighted. Weighting factors could be dependant on a specific customer's priorities, specific mission considerations, as well as the overall contribution to crew survivability that a particular requirement affects. Each requirement will contribute to the calculation of a crashworthiness index. A minimum acceptable crashworthiness index will be based on MIL-STD-1290A requirements.

6.1.1 Design Impact Conditions

Design impact conditions include the type of surface and the kinematics of the aircraft. Minimum requirements (Table 6.1.1-1) are based on MIL-STD-1290A requirements for Class IV vehicles. MIL-STD-1290A gives the specific conditions of each crash scenario and they will not be outlined here. Meeting these requirements will provide a CI of XXX, calculated as follows:

$$CI_{\min}^{DI} = \sum_{n=1}^{7} CI_n(\Delta V)$$

Where:

CI^{DI}_{min} = minimum crashworthiness index based on impact conditions.

n = condition number

$CI_n(\Delta V)$ = The CI of a specific condition as a function of the velocity change

Condition number	Impact Direction (2)	Object Impact	Velocity Change (ft/sec)	Pitch	Roll	Yaw	Coord System ?
1	Longitudinal (cockpit)	Rigid vertical barriers	20	0	0	0	AC
2	Longitudinal (cabin)		40	0	0	0	AC
3	Vertical (1)	Rigid horrizontal surface	42	$+15^0/-5^0$	$\pm 10^0$	0	Ground
4	Lateral, Type I		25	0	0	0	AC
5	Lateral, Type II		30	0	0	0	AC
6	Combined high angle Vertical (1)	Rigid horrizontal surface	42	$+15^0/-5^0$	$\pm 10^0$	0	Ground
	Longitudinal		27	$+15^0/-5^0$	$\pm 10^0$	0	Ground
7	Combined low angle Vertical (1)	Plowed soil	14	-5^0	$\pm 10^0$	$\pm 20^0$	Ground
	Longitudinal		100	-5^0	$\pm 10^0$	$\pm 20^0$	Ground

(1) For the case of retracted landing gear the seat and airframe combination shall have a vertical crash impact design velocity change capability of at least 26 ft/sec.

(2) Table 1 currently defined Impact Direction as aircraft axis. Figure 3 implies ground coord system. ACSDG (vol 1, pg 64) defines vertical impacts with respect to ground.

This work was conducted under the Full Spectrum Crashworthiness Program for AATD.

Table 6.1.1-1 - Minimum Acceptable Requirements Based on MIL-STD-1290A

Other requirements can be met to increase CI^{DI}. These include meeting requirements on other surfaces (e.g. water, soils of various CBR), expanding requirements for conditions 1-7 (e.g. increase ΔV, impact angle), and expanding the envelope for impact angles from those outlined in MIL-STD-1290A. The ability to substantiate survivability over a range of surfaces such as hard and soft soils (Figure 6.1.1-1) and water (Figure 6.1.1-2) will increase the CI. For other classes of vehicles, objective assessment of the crashworthiness qualities needs to be made to determine a minimum CI.

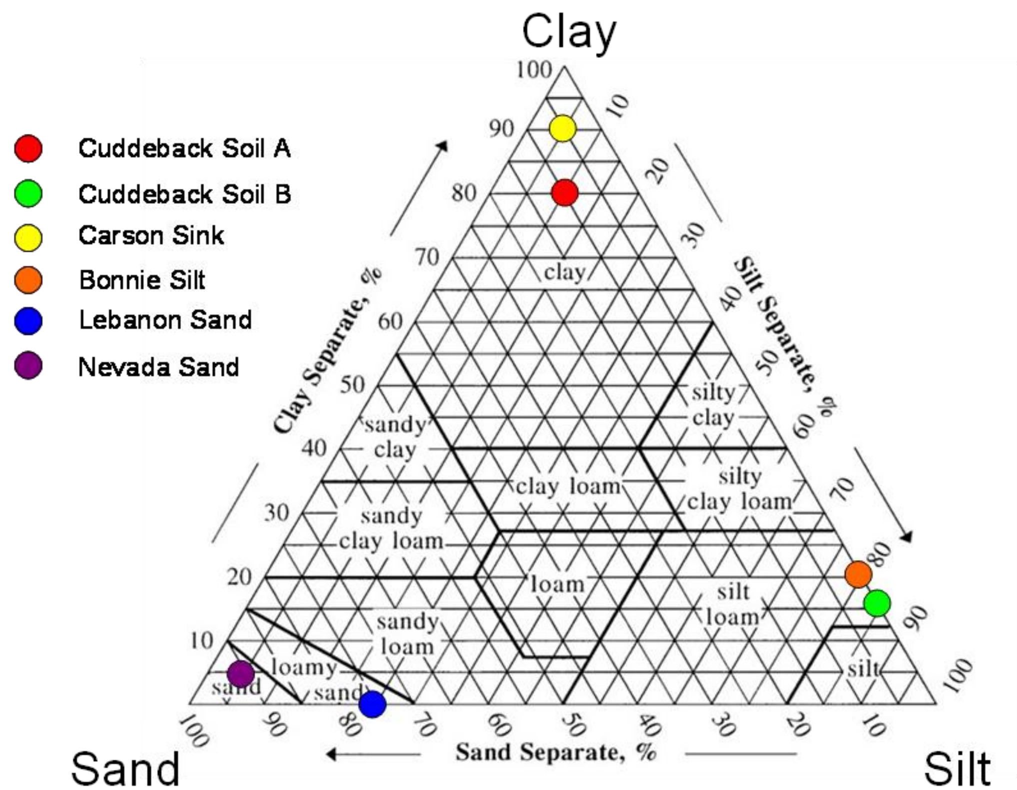


Figure 6.1.1-1 – Three soil ranges

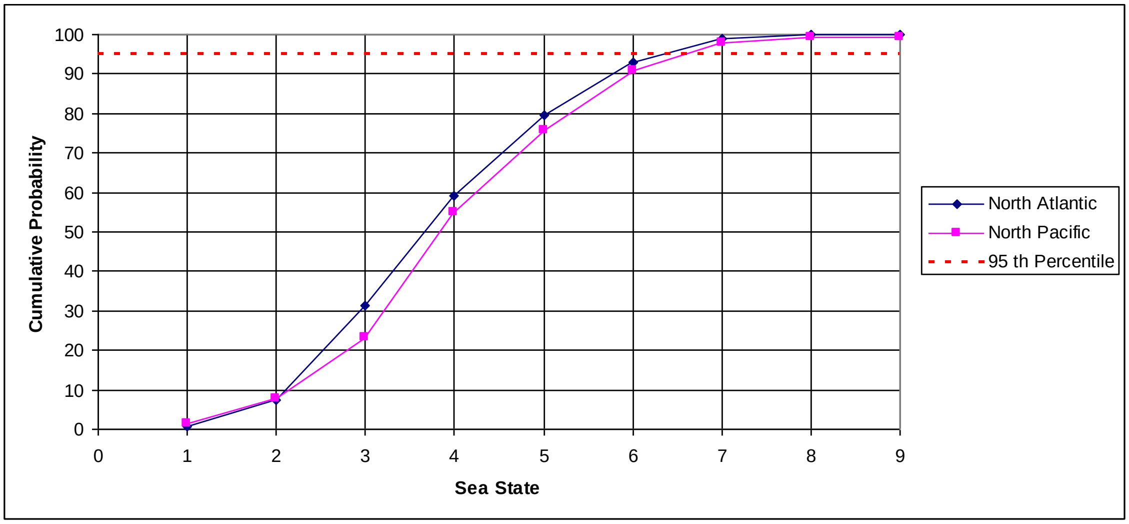


Figure 6.1.1-2 – Sea state requirements

6.1.2 Attitude Envelope

The ability to substantiate that a system is survivable within an attitude (roll, pitch, yaw) at various impact velocities will also increase the CI. Based on historical data, substantiating a system to be survivable anywhere within a velocity envelope (Figure 6.1.2-1) will significantly improve the CI. The MIL-STD-1290A requirements are point designs inside the velocity envelope. Substantiation beyond this envelope, though potentially beneficial will minimally affect the CI as historical data does not indicate scenarios outside of this envelope are likely. Notwithstanding, a system that operates at higher forward velocities by design (e.g. tiltrotor) or by mission (e.g. attack) may require substantiation to a higher longitudal velocity as the likelihood of longidual impact at greater velocity is more likely.

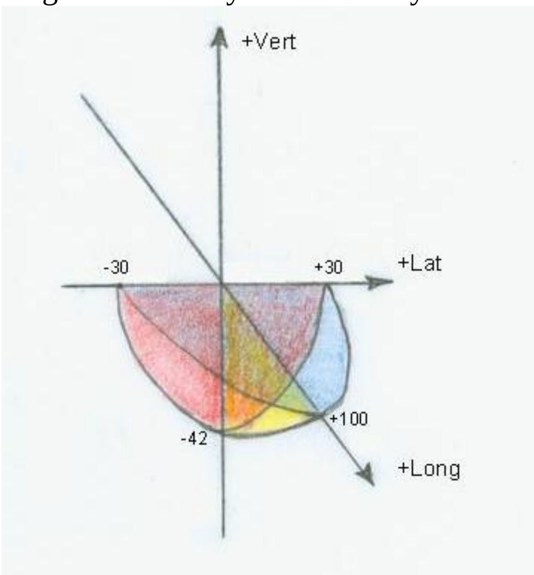


Figure 6.1.2-1 – Velocity Ellipsoid Envelope

6.2 Preliminary Occupant Protection Requirements

Occupant protection requirements are being developed and the following is not yet complete. Notional protection requirements are described below that could form the basis for the final requirements.

6.2.1 Injury Risk Due to Occupant Loads

Cervical forces and moments are to be used to evaluate injury to the head/neck, torso acceleration is used to evaluate injury to the chest, lumbar load is used to evaluate injury to the spinal column, and tibia and arm loads are used to evaluate injury to the arms and legs from impact and crash events as defined in test conditions in section XX.

6.2.2 Neck Tension Limits

The maximum limits (major injury) for dynamic neck tension (lifting forces) at the occipital condyles (C0-C1, upper neck) and cervical vertebrae (C7-T1, lower neck) are defined in the following table:

Note: Use linear interpolation for intermediate values in force and time duration

Small Female Hybrid III Type Manikin (103 to 118 lbs)		Mid-Size Male Hybrid III Type Manikin		Large Male Hybrid III Type Manikin (200 to 245 lbs)	
Duration (ms)	Tension **at C0-C1 & C7-T1 (lbs)**	**Duration (ms)**	**Tension at C0-C1 & C7-T1 (lbs)**	**Duration (ms)**	**Tension at C0-C1 & C7-T1 (lbs)**
5	414	5	618	5	761
31	414	35	618	37	761
40	200	45	320	48	450
80	200	80	320	80	450

Maximum Allowable Neck Tension Force and Duration Limits against specific Occupant sizes

6.2.3 Neck Compression and Shear Force Limits

The maximum acceptable cervical compression and shear force limits are defined in the following table:

Note: Use linear interpolation for intermediate values in force and time duration

Small Female Hybrid III Type Manikin (103 to 118 lbs)		Mid-Size Male Hybrid III Type Manikin		Large Male Hybrid III Type Manikin (200 to 245 lbs)	
Duration (ms)	**Compression at C0-C1 & C7-T1 (lbs)**	**Duration (ms)**	**Compression at C0-C1 & C7-T1 (lbs)**	**Duration** (ms)	**Compression at C0-C1 & C7-T1 (lbs)**
5	519	5	790	5	979
27	200	30	320	32	450
80	200	80	320	80	450
Duration (ms)	**Resultant Shear at C0-C1 (lbs)**	**Duration (ms)**	**Resultant Shear at C0-C1 (lbs)**	**Duration (ms)**	**Resultant Shear at C0-C1 (lbs)**
5	405	5	625	5	777
20	225	25	337	28	414
29	225	35	337	39	414
37	165	45	247	50	304
80	165	80	247	80	304
Duration (ms)	**Resultant Shear at C7-T1 (lbs)**	**Duration (ms)**	**Resultant Shear at C7-T1 (lbs)**	**Duration (ms)**	**Resultant Shear at C7-T1 (lbs)**
5	810	5	1250	5	1554
20	450	25	674	28	828
29	450	35	674	39	828
37	330	45	494	50	608
80	330	80	494	80	608

Maximum Allowable Neck Compression & Shear Force Limits against specific Occupant sizes

6.2.4 Combined Neck Moment and Load Limits

The maximum combined cervical force and moment limit, expressed as Neck Injury Criteria (Nij), is 0.5, as measured at the occipital condyles (C0-C1). The maximum Nij as measured at the cervical vertebrae (C7-T1) is 1.5. Nij is not applied for pure tension or compression. Nij is calculated from the following equation:

Note: The resultant of each sub-component of the Nij expression is positive.

$$N_{ij} = \left|\left(\frac{F_z}{F_{\text{int}}}\right)\right| + \left|\left(\frac{M_y}{M_{\text{int}}}\right)\right|$$

where:
F_z is the axial tension/compression load
F_{int} is the critical intercept load (defined in table below)
M_y is the flexion/extension bending moment.
M_{int} is the critical intercept moment (defined in table below)

	Small Female Hybrid III Type Manikin (103 to 118 lbs)	Mid-Size Male Hybrid III Type Manikin	Large Male Hybrid III Type Manikin (200 to 245 lbs)
Tension (lb) (+F_z)	964	1530	1847
Compression (lb) (-F_z)	872	1385	1673
Flexion (in-lb) (+My)	1372	2744	3673
Extension (in-lb) (-My)	593	1195	1584

Critical Intercept Values for Nij Calculation at C0-C1 and C7-T1 for specific Occupant Sizes

6.2.5 Neck X and Z Moment Limits

To evaluate neck lateral bending (Mx) and rotation (Mz), the Neck Moment Index (NMI) will be calculated. The maximum allowable NMIx, is 0.5, as measured at the occipital condyles (C0-C1) and 1.5 as measured at the cervical vertebrae (C7-T1). The maximum allowable NMIz, is 0.5, as measured at the occipital condyles (C0-C1) and 1.0 as measured at the cervical vertebrae (C7-T1). NMI is calculated using the following equation:

$$NMI_i = \left|\frac{M_i}{M_{iLIM}}\right|$$

where:
NMI_i is NMIx or NMIz
M_i is Mx or Mz
M_{iLIM} is the Mx or Mz limit (defined in the table below)

	Small Female Hybrid III Type Manikin (103 to 118 lbs)	Mid-Size Male Hybrid III Type Manikin	Large Male Hybrid III Type Manikin (200 to 245 lbs)
Lateral Bending (in-lb) (+/- Mx)	593	1195	1584
Rotation (in-lb) (+/- Mz)	593	1195	1584

Values for NMI Calculation at C0-C1 and C7-T1 for specific Occupant Sizes

6.2.6 Head Impact Tolerance

The resultant acceleration at the center of gravity of the head shall be such that the Head Injury Criterion (HIC):

$$HIC = \left[\frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} a dt \right]^{2.5} (t_2 - t_1)$$

shall not exceed 700, where a is the resultant acceleration expressed as a multiple of g (the acceleration of gravity), and t1 and t2 are any two points in time during the acceleration of the head, which are not separated by more than a 15 millisecond interval.

6.2.7 Thoracic Evaluation

The maximum chest acceleration is listed in the below table.

	Small Female Hybrid III Type Manikin (103 to 118 lbs)	Mid-Size Male Hybrid III Type Manikin	Large Male Hybrid III Type Manikin (200 to 245 lbs)
Spine acceleration (G)	73	60	54

Maximum Acceleration Values for Chest Calculation for specific Occupant Sizes

6.2.8 Tibia Load Limits

The maximum combined tibial force and moment limit, expressed as the Tibia Index (TI), is 1.0. TI is calculated from the following equation:

$$TI = \frac{M(t)}{MC} + \frac{P(t)}{PC}$$

where:
M(t) is the resultant bending moment
P(t) is the absolute value of the corresponding axial compressive force at time t
MC is the critical intercept moment (defined in table below)
PC is the critical intercept force (defined in table below)

	Small Female Hybrid III Type Manikin (103 to 118 lbs)	Mid-Size Male Hybrid III Type Manikin	Large Male Hybrid III Type Manikin (200 to 245 lbs)
Moment (Nm)	115	225	307
Compression (N)	22.9	35.9	44.2

Critical Intercept Values for TI Calculation for specific Occupant Sizes

6.2.9 Arm Load Limits

The maximum Arm force and moment limits are defined in the below table.

	Small Female Hybrid III Type Manikin (103 to 118 lbs)	Mid-Size Male Hybrid III Type Manikin	Large Male Hybrid III Type Manikin (200 to 245 lbs)
Moment (Nm)	TBD	TBD	TBD
Compression (N)	TBD	TBD	TBD

Maximum Values for Arm Injury for specific Occupant Sizes

6.2.10 Lumbar Load Limits

The maximum Lumbar force limits are defined in the below table.

	Small Female Hybrid III Type Manikin (103 to 118 lbs)	Mid-Size Male Hybrid III Type Manikin	Large Male Hybrid III Type Manikin (200 to 245 lbs)
Compression (N)	1000	1500	2200

Maximum Values for Lumbar Injury for specific Occupant Sizes

6.3 <Cost – Benefit requirements are TBD> Note: Research has shown that the initial cost and weight increases associated with incorporating crash protection features are offset by the cost-benefits of reduced personnel injury and reduced structural damage over an aircraft's life cycle. Consequently, new generation aircraft are now procured under a requirement to implement a systems design approach in the development of occupant crash protection.

6.4 Design for System Crashworthiness (Preliminary Ideas). How each of these elements affects the overall CI is still TBD. A crashworthiness requirement should be tailorable to the specific aircraft missions, performance requirements, and the envirionment that the aircraft will be operating in.

6.4.1 Elements of System Crashworthiness Design

6.4.1.1 Occupant Protection

6.4.1.1.1 Forces and Accelerations

6.4.1.1.2 Airframe Intrusion.

The structure of the aircraft should protect the occupants in a crash and deform in a way that is predictable and controlled so that forces felt by the occupants are endurable. The structure design should minimize the inward buckling that would affect the occupant space and prevent component failures that may cause mechanical insult to the occupant.

6.4.1.1.3 Flailing.

Injury due to flailing body parts needs to be minimized by providing an environment for the occupant where contact with the aircraft structure is minimized.

6.4.1.1.4 Projectiles

Airframe subsystems such as overhead circuit breaker panels should be designed to remain in place during crash scenarios. Security of ancillary equipment such as NBC blower mortar , weapons, survival kits, fire extinguishers, etc., have guaranteed location retention with full accessibility.

6.4.2 <Intentionally left blank>

This work was conducted under the Full Spectrum Crashworthiness Program for AATD.

6.4.3 Post-Crash Survival.

Performance and functional requirements to assist the design and qualification of an aircraft system that allows safe egress in a crash event. (Ground, water, cold, snow)

6.4.3.1 Design for Egress

An adequate number of exits should be provided with sufficient size in order to give occupants a variety of locations to egress the rotorcraft in case some exits are blocked due to the aircraft's position after the crash. Emergency exits should be clearly identified.

6.4.3.1.1 Airframe.

For safe egress from the crashed or ditched vehicle, the airframe should be designed to provide or retain unobstructed paths to vehicle hatches, doors, or portals - a minimum number of which should remain unobstructed due to vehicle orientations or submersion after the crash event. Hatches and doors should retain sufficient integrity so that they remain operable. In the event of ditching or crash into deep water, the airframe should provide stable buoyancy sufficient to prevent sinking, and to prevent inversion to the maximum extent possible.

6.4.3.1.2 Components.

The components, and their constituent materials, of the interior of the occupied space should retain sufficient integrity so they do not present sharp, hot, electrically conductive, or otherwise hazardous obstruction to safe egress and escape. Should there be fire, the materials of the airframe should not emit toxic fumes or smoke and should be generally fire suppressive in nature.

6.4.3.1.3 Lighting.

Visual cueing that leads to hatches, exits, doors, handholds, guide bars.

6.4.3.2 Safing

In order to prevent subsequent injury during the egress and escape period, the aircraft and systems should facilitate or automatically accomplish safing from hazards to egress. Electrical power should be terminated. Emergency lighting and fire suppression systems and/or extinguishers should function as necessary. Major components of the rotor system, hydraulics, APU, etc., should either depart the airframe or come to complete stop as soon as possible.

6.4.3.3 Communications

6.4.3.3.1 Emergency Locator Transmitter

6.4.3.3.2 Crash Resistant Event Recorder

6.4.3.3.3 3D Audio Cuing

6.4.3.3.4 Visual Cuing

This work was conducted under the Full Spectrum Crashworthiness Program for AATD.

Place cards and markings designed to aid personnel in locating closest egress and safety gear.

6.4.3.4 Survival Gear

Provisions and gear for post crash survival should be easily available to egressed passengers. Life rafts, personal flotation devices, shelters, and other equipment should be deployable or retrievable from outside the airframe or automatically dispense or deploy as appropriate. The survival gear should be stowed in a manner that preserves the function and utility of the gear for emergency use.

6.4.3.5 Seats and Restraint Systems

Crashworthy seating design will guarantee desirable operation through the kinematics and dynamics of crash scenarios, assuming the seat is designed to travel into the floor bucket.

6.5 Special Requirements

6.5.1 Cargo Retention

Restraints will keep the cargo from shifting while in flight even in extreme weather conditions. If the structure of the fuselage and floor is not strong enough to withstand the cargo crash loads, load limiters shall be used to limit the loads transmitted to the structure.

6.5.2 Litter Retention

Shall be designed to withstand the most common impacts that can be severe in nature by providing as much contact area and support as practical.

6.5.3 Off-design Conditions

7. Rotorcraft Crash Data Analysis

7.1 Analysis Foundation

The analysis for this section is taken directly from the final report (Ref. A1) for the Research, Development and Engineering Command (RDECOM) titled *Rotorcraft Crash Data Analysis*, RDECOM TR 09-D-45, Section 2, Summary of Effort Conducted. The analysis is based on an investigation of US Army rotorcraft mishap data.

This investigation gathered and analyzed detailed information describing aircraft crashes and their outcomes for the purpose of revising the crashworthiness design criteria applied to US military rotorcraft. The study covered nine aircraft types. Two generations of attack helicopters were studied: AH-1 and AH-64. Two generations of utility helicopters were studied: UH-1 and UH-60. Three observation helicopters were studied: OH-6, OH-58A/C and OH-58D. The OH-58D was studied as a separate aircraft from the OH-58A/C because the D-model is substantially redesigned compared to the A and C models. In particular the main rotor design is fundamentally different. The CH-47 is a twin main rotor helicopter and the largest helicopter in the study. The C-23 was initially included in the study with the expectation that this light, fixed wing aircraft could serve as a surrogate for the V-22 aircraft in airplane mode. However, there were only three

C-23 crashes and all three proved to be non-survivable and hence no information on crashworthiness could be extracted.

The detailed data on the crashes came from the US Army Aviation Safety Database at the Combat Readiness Center. The information from the database included parameters describing the aircraft and its flight prior to the emergency, parameters describing the kinematics of the crash, and parameters describing the outcome of the crash in terms of damage to the aircraft and the injuries to the occupants.

7.2 Crash Analysis Methodology

The primary interest of this investigation is to improve the crashworthiness of aircraft; therefore, the first step was to select the crashes out of all the mishaps recorded in the database. This selection process was accomplished by reviewing all of the narratives and checking the description in the narrative against the impact velocity data. A mishap was defined to be a crash, if the aircraft obviously impacted the terrain or an object AND there was measurable damage to the aircraft. In cases where the damage was so minor that the crew continued to fly the aircraft, the event was not a crash. The database differentiates between in-flight impacts and terrain impacts. In-flight impacts are those where the aircraft impacts an obstacle above the terrain level and then subsequently lands or crashes into the terrain (for brevity these crashes are referred to as either IT&TA crashes or post-obstacle crashes). The author anticipated that crashes following an in-flight impact would have different kinematic characteristics than the crashes that occurred directly into terrain (crashes directly into the terrain are referred to either as T crashes or direct to terrain crashes). Consequently, the two types of crashes were identified, and the data maintained in separate groups so that the crash kinematics and injury outcomes could be compared.

Once each mishap had been identified as to whether or not it was a crash, queries were written to extract the desired data for only the events identified as crashes. The queries were executed to extract the data by aircraft type and crash type, so each aircraft had two queries in each data category. Each query was written to extract one category of data such as kinematic parameters. For the post-obstacle crashes two kinematic queries are needed one to extract the kinematic information for the terrain impact and one to extract the kinematic information for the in-flight impact. A pair of queries for each aircraft type extracted data about the aircraft in general, the mission, the phase of flight, gross weight, altitude and the number of people on board. Another pair of queries was written to extract data describing the damage to the aircraft in terms of hull crush, and dislocation of major components. Yet another pair of queries gathered data on the crash site, including the nature of the surface, a description of the general terrain, and the obstacles in the vicinity of the landing site. A pair of queries gathered data describing post-crash fires and the consequential burn injuries. Data were also gathered on the protective equipment available to the occupants, its use, and its performance. A pair of queries gathered information on the injuries to the occupants and the roles of these occupants. Logic statements were used to select and manipulate values while mathematical calculations could be applied to the quantitative data. The data in this early stage of analysis are presented as graphs and tables in an extensive appendix to the final report.

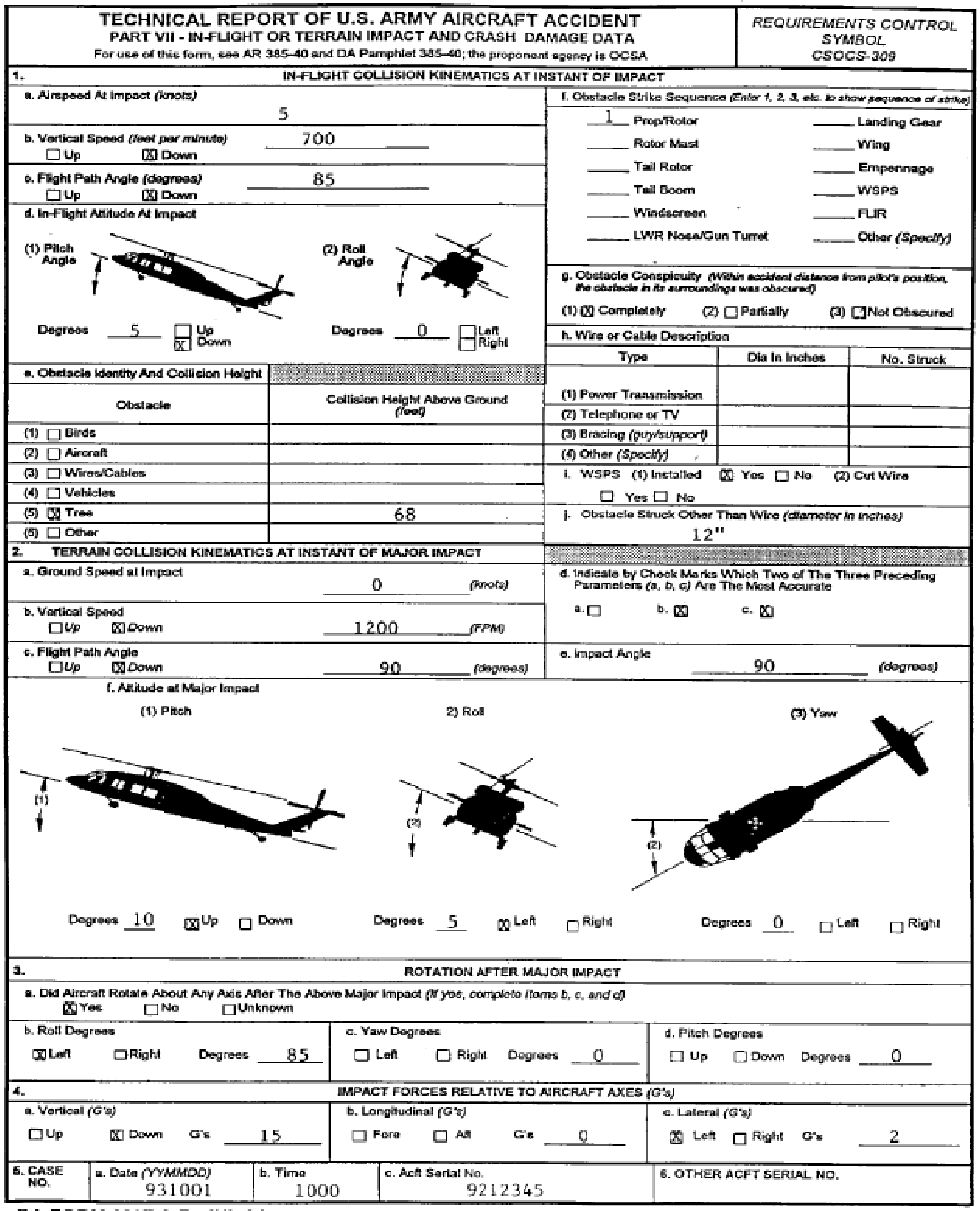
7.2.1 Angle Sequence Methodology

The accident mishap reporting form, DA Form 2397-6-R, requires that the pitch, roll, and yaw must be entered in to Block 2f. (Figure 6.4.3.3.4-1) When converting from the ground to the airframe axis system, SAFE chose to use the Euler angle sequence of roll first, pitch second, and yaw third to define the matrix transformation order. However, one might assume that the investigators were taught to use a sequence of pitch, roll, and then yaw from the order that the Euler angles are recorded in the accident report. Others would contend that using these angular terms imply a standard convention of yaw first, pitch second, and roll third.

Without consideration of any specific convention, there are six possible angular sequences of yaw, pitch, and roll. Several studies were conducted to determine the relative effect in mishap statistics by considering the six different matrix transformations. The first study tabulated the 95th cumulative percentile of downward vertical velocity for survivable and partially survivable mishaps into terrain (T, S=1, 2). (Table 7.2.1-1) The fleet statistics indicated a 95th percentile varying from 41.4 to 45.0 ft/s. If these values were used to define a vertical crash design impact velocity for future rotorcraft, the energy associated with the impact could differ by as much as 18% since the energy is a function of the velocity squared. That is thought to be significant.

Table 7.2.1-1 95th Percentile Downward Vertical Impact Velocity (T, S=1,2)

Matrix Order	Vertical Velocity (ft/s)	Rotation Order 1st	2nd	3rd
[GP][GR][GY]	45.0	yaw	roll	pitch
[GR][GY][GP]	44.9	pitch	yaw	roll
[GR][GP][GY]	44.9	yaw	pitch	roll
[GY][GP][GR]	41.7	roll	pitch	yaw
[GP][GY][GR]	41.5	roll	yaw	pitch
[GY][GR][GP]	41.4	pitch	roll	yaw



TECHNICAL REPORT OF U.S. ARMY AIRCRAFT ACCIDENT
PART VII - IN-FLIGHT OR TERRAIN IMPACT AND CRASH DAMAGE DATA
For use of this form, see AR 385-40 and DA Pamphlet 385-40; the proponent agency is OCSA

REQUIREMENTS CONTROL SYMBOL CSOCS-309

1. IN-FLIGHT COLLISION KINEMATICS AT INSTANT OF IMPACT

a. Airspeed At Impact *(knots)*: 5

b. Vertical Speed *(feet per minute)*: 700 ☐ Up ☒ Down

c. Flight Path Angle *(degrees)*: 85 ☐ Up ☒ Down

d. In-Flight Attitude At Impact
(1) Pitch Angle — Degrees 5 ☐ Up ☒ Down
(2) Roll Angle — Degrees 0 ☐ Left ☐ Right

e. Obstacle Identity And Collision Height

Obstacle	Collision Height Above Ground *(feet)*
(1) ☐ Birds	
(2) ☐ Aircraft	
(3) ☐ Wires/Cables	
(4) ☐ Vehicles	
(5) ☒ Tree	68
(6) ☐ Other	

f. Obstacle Strike Sequence *(Enter 1, 2, 3, etc. to show sequence of strike)*
1 Prop/Rotor; ___ Rotor Mast; ___ Tail Rotor; ___ Tail Boom; ___ Windscreen; ___ LWR Nose/Gun Turret; ___ Landing Gear; ___ Wing; ___ Empennage; ___ WSPS; ___ FLIR; ___ Other *(Specify)*

g. Obstacle Conspicuity *(Within accident distance from pilot's position, the obstacle in its surroundings was obscured)*
(1) ☒ Completely (2) ☐ Partially (3) ☐ Not Obscured

h. Wire or Cable Description

Type	Dia In Inches	No. Struck
(1) Power Transmission		
(2) Telephone or TV		
(3) Bracing *(guy/support)*		
(4) Other *(Specify)*		

i. WSPS (1) Installed ☒ Yes ☐ No (2) Cut Wire ☐ Yes ☐ No

j. Obstacle Struck Other Than Wire *(diameter in inches)*: 12"

2. TERRAIN COLLISION KINEMATICS AT INSTANT OF MAJOR IMPACT

a. Ground Speed at Impact: 0 *(knots)*

b. Vertical Speed ☐ *Up* ☒ *Down*: 1200 *(FPM)*

c. Flight Path Angle ☐ *Up* ☒ *Down*: 90 *(degrees)*

d. Indicate by Check Marks Which Two of The Three Preceding Parameters *(a, b, c)* Are The Most Accurate: a. ☐ b. ☒ c. ☒

e. Impact Angle: 90 *(degrees)*

f. Attitude at Major Impact
(1) Pitch — Degrees 10 ☒ Up ☐ Down
2) Roll — Degrees 5 ☒ Left ☐ Right
(3) Yaw — Degrees 0 ☐ Left ☐ Right

3. ROTATION AFTER MAJOR IMPACT

a. Did Aircraft Rotate About Any Axis After The Above Major Impact *(If yes, complete items b, c, and d)* ☒ Yes ☐ No ☐ Unknown

b. Roll Degrees ☒ Left ☐ Right Degrees 85

c. Yaw Degrees ☐ Left ☐ Right Degrees 0

d. Pitch Degrees ☐ Up ☐ Down Degrees 0

4. IMPACT FORCES RELATIVE TO AIRCRAFT AXES *(G's)*

a. Vertical *(G's)* ☐ Up ☒ Down G's 15

b. Longitudinal *(G's)* ☐ Fore ☐ Aft G's 0

c. Lateral *(G's)* ☒ Left ☐ Right G's 2

5. CASE NO.	a. Date *(YYMMDD)*	b. Time	c. Acft Serial No.	6. OTHER ACFT SERIAL NO.
	931001	1000	9212345	

DA FORM 2397-6-R, JUL 94

Figure 6.4.3.3.4-1 Sample Section of Accident Mishap Report

7.3 Crash Analysis Results

The largest difference between this study and previous similar studies is the separation of the crashes into two types on the basis of whether the aircraft had made prior contact with some obstacle. In approximately 30 percent of the crashes studied, the aircraft struck some obstacle above ground level prior to impacting the "ground." These obstacles included other aircraft, wires, buildings, vehicles and most frequently trees. In some cases striking the obstacle was itself the cause of the crash as in a wire strike; while in other cases the impact was coincidental to an emergency approach to the ground. It was expected at the outset, that the outcomes for the "post-obstacle" crashes would be different from the crashes directly into terrain. The direct terrain crashes were entirely survivable in 73 percent of the events, whereas the post-obstacle crashes were entirely survivable in just 55 percent of the events. The differences in outcomes proved to be easier to reveal and quantify than the differences in crash characteristics, especially the kinematics.

This study includes data for the AH-1, the UH-1, and OH-58AC aircraft. These three aircraft accounted for 419 crashes compared with 207 crashes for the comparable, later generation aircraft: AH-64, UH-60, and OH-58D.

7.3.1 Kinematics – Velocities

The nature of the crash velocity data is such that it covers a very wide range of values. Consequently, when the means or medians are calculated, very large standard deviations result. Large standard deviations make demonstrating that statistically significant differences exist very difficult. Testing the velocity data from individual aircraft revealed only a few cases where the difference between the mean or median velocity for terrain (T) crashes was statistically different from the same velocity for the terrain impact following in-flight contact with an obstacle. (IT&TA) crashes.

7.3.2 Kinematics – Angle

Plots of the flight path and impact angle distributions show a difference between the direct terrain impacts and the post-obstacle impacts (Figure 3). The direct terrain impacts occur markedly more frequently with low flight path and low impact angles than do the post-impact crashes. In contrast, the post-obstacle crashes occur almost twice as often a near vertical flight path and impact angles than do the direct terrain crashes and at higher vertical velocity (Figure 3).

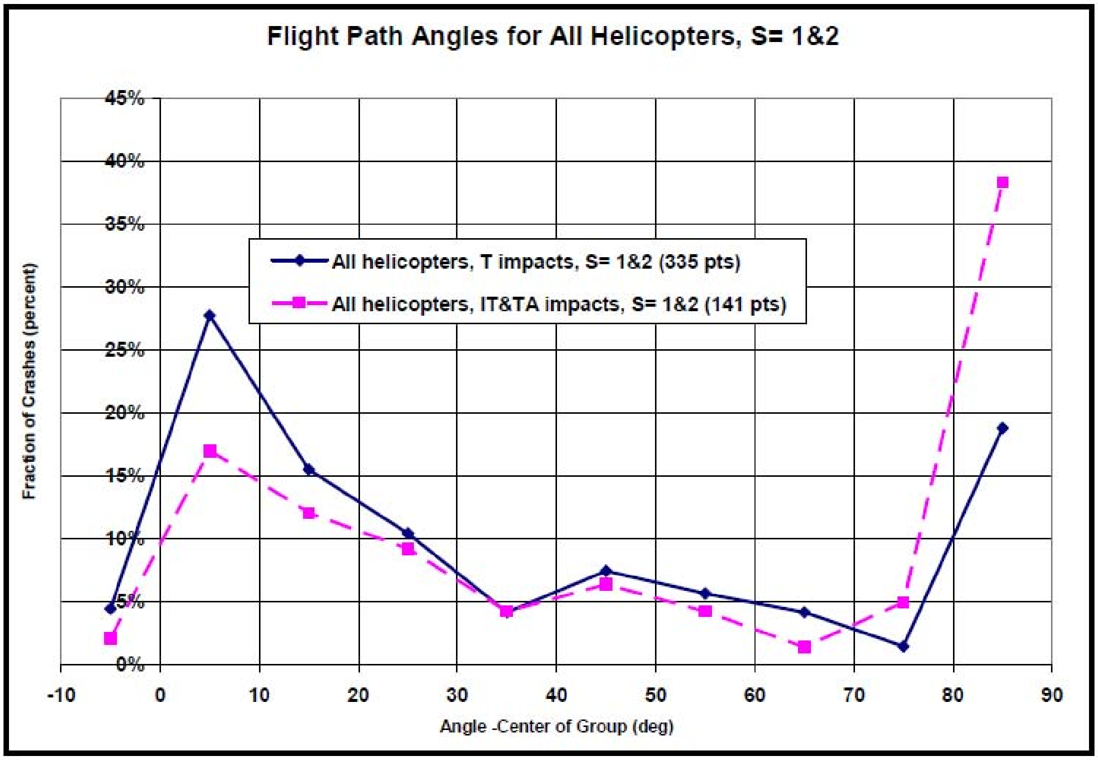


Figure 3 – Comparison of flight path angle for obstical (IT-T&TA) and non-obstical (T) crashes

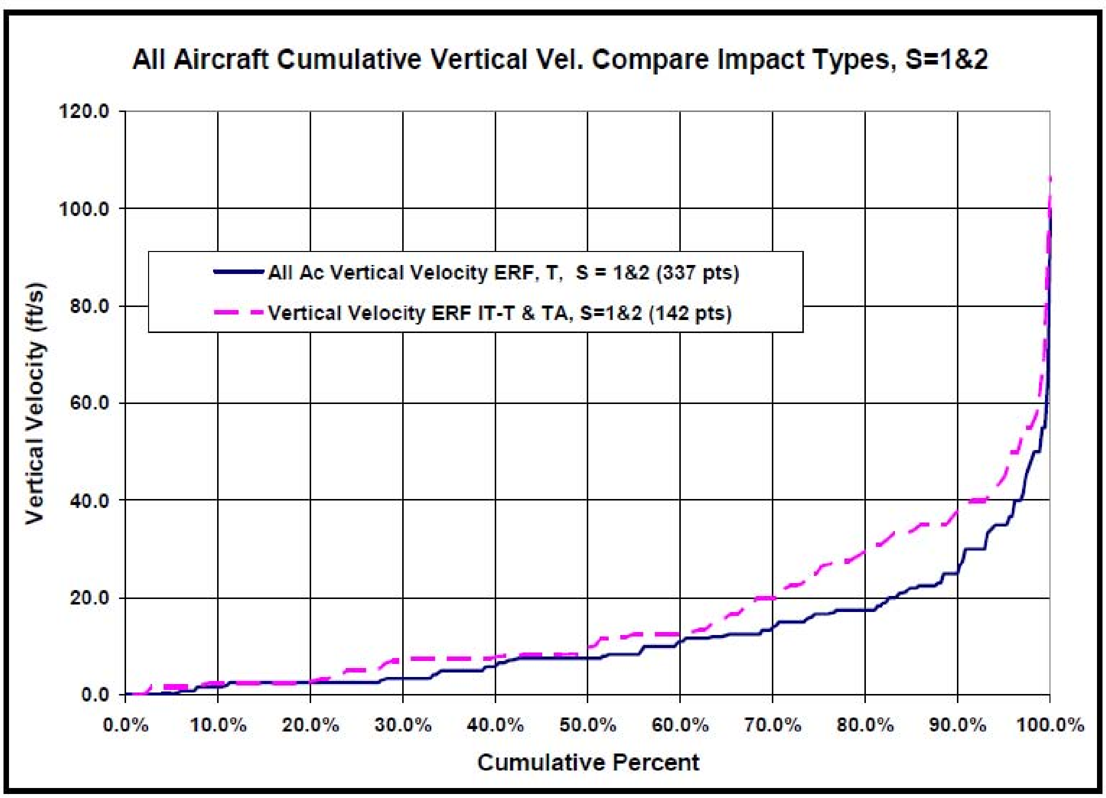


Figure 3 – Comparison of vertical velocity for obstical (IT-T&TA) and non-obstical (T) crashes

The distributions of attitude angles cluster tightly around the nominal aircraft attitude (each angle equals zero). The post-obstacle crashes exhibit a lower peak frequency at zero and a correspondingly broader distribution. In particular, the pitch angle distribution for the post-obstacle crashes is characterized by more nose down events which would tend to be more injurious for pilots and to partially neutralize the protection provided by the landing gear. The roll angle distribution for the post-obstacle has a small second peak in the frequency curve between -80 and -110 degrees (left roll). Crashes at this attitude are effectively lateral crashes on the left side. Once again, no benefit is obtained from the energy absorption strategy, which is effective for predominantly vertical crashes at nominal attitudes.

Analysis for statistical significance found that the difference between the direct terrain crashes and the post-obstacle crashes were statistically significant for the pitch angle distributions of individual aircraft types and of all the aircraft combined. The more frequent nose down attitude in the post-obstacle crashes was confirmed. The statistical analysis failed to find a statistical difference in the roll angle means or medians, but it did confirm that the post-obstacle crashes showed a broader distribution of frequencies. Likewise for the yaw angle.

7.3.3 Operational Information

This data was perhaps the least revealing area studied. The expectation for analyzing this data was to reveal information about the events leading up to the crash. Unfortunately this portion of the database is less well populated than other areas and the data that are present were not revealing. For example the phase of operation is reported at three times in the crash sequence: as planned, at emergency and at termination. The as-planned datum is seldom provided. For all three of these fields combined, the three most commonly reported phases are landing (27 percent), autorotation (12 percent), and cruise (11 percent). The most useful phase information appears to be that labeled as Phase at Emergency. This field is the closest information available to identifying the operation mode at the onset of the emergency. At the time of the emergency, cruise (19.4 percent) is the most commonly reported phase, followed by landing (14.3 percent). Combining the three low level flight regimes “low level,” “NOE,” and “contour” accounts for 12.1 percent of the crashes and combining IGE hover with OGE hover accounts for a further 11.4 percent.

7.3.4 Impact Severity

The data on the impact forces were difficult to analyze. In many cases the values of the standard deviations were larger than the mean values due to a few extraordinarily large values reported. The mean values incorporated both positive and negative values which tended to bring the mean values closer to zero. The fraction of all crashes with impact directions opposite to the conventional direction was surprising.

Cumulative percentile plots were created using absolute values of the impact severities and these clarified the analysis significantly (Figure 5). The plots revealed a smooth increase in the crash severity up to about 40 G. Beyond this level, large jumps in the severity values appear, indicating that there may be some difficulty in estimating the actual values. Average values were calculated using the absolute values and these means proved quite revealing. Comparing the mean absolute values for the direct terrain crashes to the means for the post-obstacle crashes, the post-obstacles crashes generally had equal or higher values than the direct terrain impacts. This difference is one clear indicator of why the post-obstacle crashes are more injurious than the direct terrain crashes.

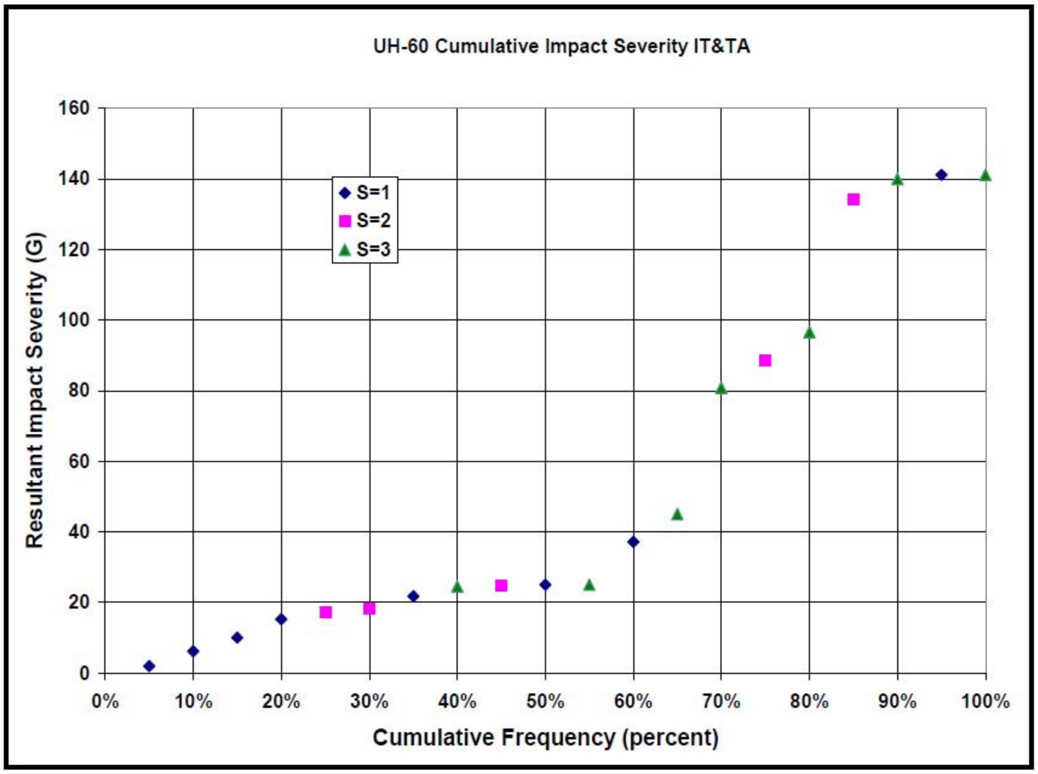


Figure 5 – Example of impact severity plot

7.3.5 Airframe Damage

The airframe damage is recorded as three or four levels of displacement for 18 regions around the airframe. The damage at each region is also coded for whether that damage contributed to an injury or not. The data are presented in the form of aircraft maps (Figure 6). These maps report the damage frequencies for each region of the aircraft. For each damage level in a region, the frequency that damage in that region led to an injury is reported. The frequency is reported as a percentage of the crashes by that aircraft type.

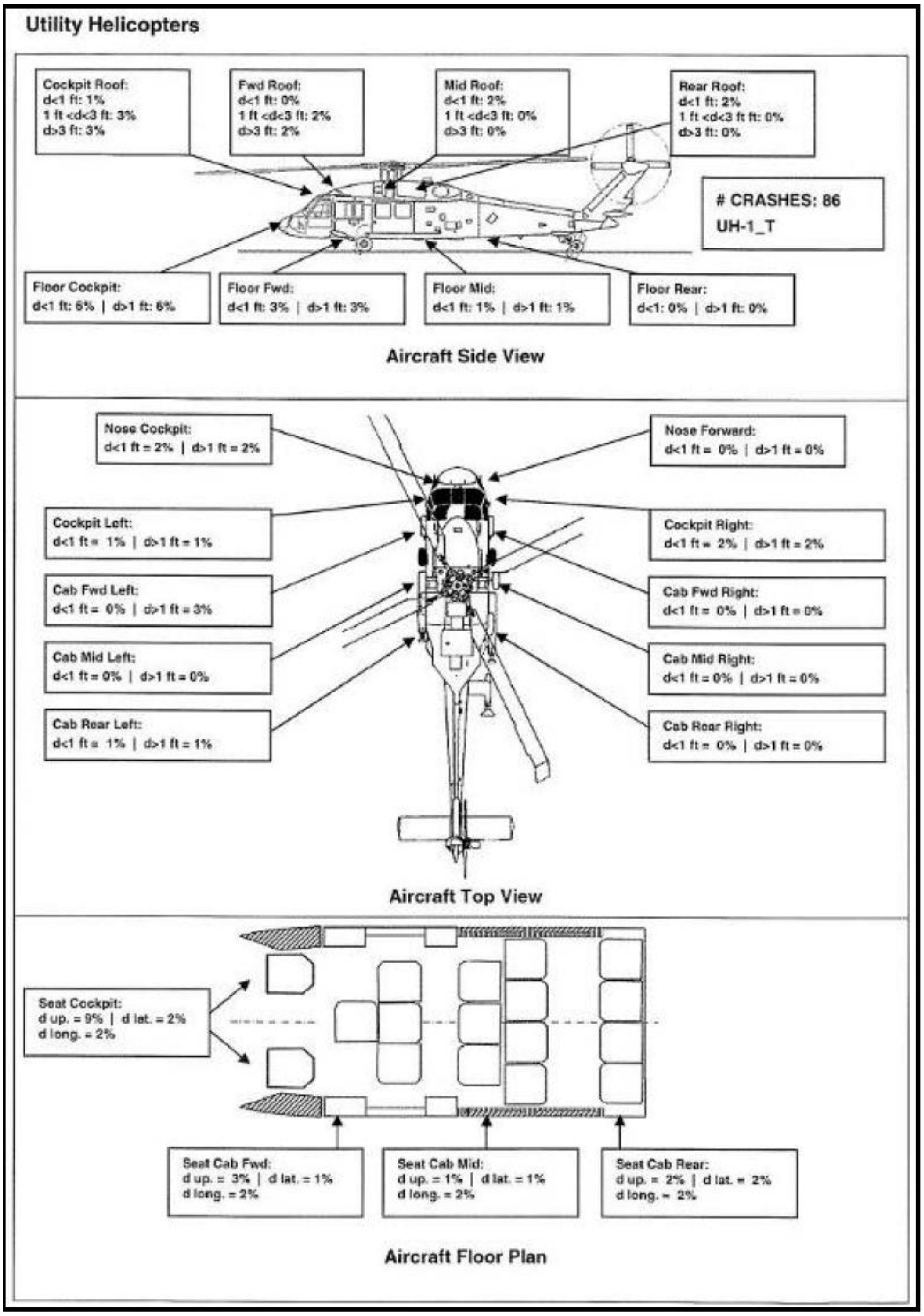


Figure 6- Example of a damage map

7.3.6 Retention of High Mass Items

For the AH-64, comparing the frequency that high mass items are displaced in direct terrain crashes to the frequency for post-obstacle crashes reveals more frequent displacements for the post-obstacle crashes.

7.3.7 Impact Surface

An impact surface was reported for approximately 89 percent of all the crashes analyzed. Sixty-six percent of the crashes where the surface was reported occurred onto sod which is a term for a broad range of unprepared, natural surfaces. Just 16 percent of crashes occurred onto prepared surfaces. These relative frequencies remained consistent between both survivable and non-survivable crashes and between crashes directly to terrain and post-obstacle crashes.

7.3.8 Crash Site Obstacles

Obstacles at the crash site are not necessarily those impacted, but are obstacles in the vicinity of the crash site. Trees were reported as obstacles near 40 percent of the sites for survivable and partially survivable crashes directly into terrain. Trees were reported near 56 percent of sites for non-survivable crashes directly into terrain. Trees were reported as obstacles near 72 percent of the sites for survivable and partially survivable post-obstacle crashes. The corresponding frequency for non-survivable crashes was reported as 60 percent. The next most frequently reported obstacle is “rocks.”

7.3.9 Injury Data

The data on injuries is recorded in two tables in the database. One form is reported in the ”aircraft information” table and consists of the number of people onboard the aircraft injured at various severity levels including those without injuries. These people are identified as either civilian or military. The other form of data is reported in the “injury information” table and consists of detailed information about the injuries to each person and information about the injured person including the person’s role aboard the aircraft. The number of personnel covered in these two data sets did not correlate well. The table with detailed injury and role information did not include the uninjured personnel, nor did it appear to include all personnel with the lower severity injuries. Nor did the number of people in major injury categories agree from one table to the other. The data from each table were treated separately and data from each table were presumed to be at least consistently reported between aircraft types within each table.

Injury maps were created similar to those originally presented in the Aircraft Crash Survival Design Guide. These maps display the frequency of injury to various regions of the human body. The frequencies are reported as the fraction of injuries to the body region as a percentage of the number of injuries reported. An injury map is presented for all personnel combined and one map is presented for each of three personnel roles on the aircraft: pilots, non-pilot crew, and passengers. A second set of injury maps was created that reports the frequency of individuals injured in each body region. These maps report the fraction of individuals injured in each body region as a percentage of the number of individuals with reported injuries.

7.3.10 Injuries Due to Post-crash Fire

Sixteen of eighteen fire fatalities are attributed to just two crashes. In both crashes, non-crashworthy, auxiliary fuel systems provided the source of flammable material to sustain the fire.

7.3.11 Protection Equipment

Four pieces of protective equipment were studied: lap belt, shoulder harness, inertia reel and seat. In general, pilots, as a group, have all of these items available to them and use them. The situation in the cabin is difficult to generalize. In many cases the equipment is not available to all personnel; and even when it is available, the equipment frequently is not used. More functional failures also are reported for the cabin. Equipment usage is higher in both models of the OH-58 where the cabin is smaller and more contiguous with the cockpit than usage in the larger aircraft where the cabin and cockpit are less contiguous. In larger aircraft there is more passenger equipment usage due to the proximity of the passengers to the equipment. The difference may also be attributed to the difference in the time available to entering passengers for finding and securing their restraints.

A difference in performance by protective equipment is recorded between the direct terrain impacts and the post-obstacle impacts. With exceptions for specific devices in the attack helicopters, a higher percentage of "injuries prevented" is reported for direct terrain crashes than for post-obstacle crashes. This trend applies to all four devices and to both the cockpit and the cabin.

Aside from the low usage rates for protective equipment in the cabin, the most remarkable feature of these data is the seat performance. Twenty-one instances of pilot seats "producing injury" were reported as were ten failures to function. In the cabin, seven instances of the seat producing an injury were reported for the UH-1 and ten seat failures were reported between the UH-1 and the UH-60.

7.3.12 Transition Velocity Analysis

An analysis used previously to compare the crashworthiness of two aircraft was modified and applied in this work. The analysis identifies that velocity above which all crashes result in severe injury to <u>all</u> of the occupants. The analysis done previously used fatalities, but this work expands the criterion to include missing, totally disabled and partially disabled persons. The revised method also simplifies the approach by plotting the fraction of personnel with severe injuries for each crash rather than grouping crashes into velocity increments.

For the vertical speed, the analysis finds that the transition velocity for direct terrain crashes is generally higher than the transition velocity for post-obstacle crashes. The exceptions are the UH-1 and the AH-64. By regrouping the aircraft, by rotor technology, it became apparent that the transition velocity associated with the direct to terrain crashes may be associated with the autorotation characteristic and the rotor system configuration, whereas the transition velocity for the post-obstacle crashes is more characteristic of the structural integrity of the airframe.

The application of transition velocity analysis to the ground speed was not productive. Clear transition speeds were difficult to determine or the resulting velocities were extremely high. This result is attributed to the presence of low impact angle crashes for each aircraft type. In these type accidents, the aircraft slides out over a long distance reducing the deceleration forces to tolerable levels and allowing partial survivability. The velocities of these crashes are often widely spaced, thus making the determination of a transition velocity less meaningful. In several cases the crash with the highest calculated longitudinal velocity was a partially survivable crash rather than a non-survivable crash.

7.3.13 Regression Analysis

Two forms of regression analysis were performed: linear regression using the fraction of severe injuries as the response variable and ordinal logistic regression using the crash survivability as the response variable. Neither analysis approach achieved predictive models, that is to say models that can predict crash outcomes given the characteristics from a particular crash. However, the models have confirmed the importance of variables such as the vertical speed and ground speed and have quantified their relative importance.

While simple to run and easy to understand, the linear regression models disappointed in that the resulting models had low predictive values. One statistic generated by the regression software indicates what percent of the total variability displayed in the response variable is predicted by the regressor (input) variables. These values were generally in the ten to thirty percent range, far short of the percentages that one would hope for in a model to be considered truly predictive. These results mean either that important regressor variables are absent from the model or that the there is too much variation in the regressor variables. Many variables that were expected to be important in determining crash outcomes were found not to be statistically significant. Among the crash variables that failed to be predictive were the three attitude angles at impact, the crash type, and the disk loading. None of the aircraft design variables were found to be statistically significant either, including the rotor system, number of main rotor blades, landing gear type, or tail rotor position.

The ordinal logistic regression analysis is more complex to run and its results are far from easy to interpret. However, this model consistently found the same parameters significant and predicted similar coefficients for five of the eight aircraft types. Furthermore, the ordinal logistic model consistently included the crash type as significant in determining the survivability of a crash.

7.4 Conclusions

This study divided the crashes into two types: crashes direct-to-terrain (T) and crashes into terrain following an impact with some obstacle above ground level (IT&TA or "post-obstacle").

- Approximately 30 percent of all the crashes studied were post-obstacle crashes.
- The survivability of the two crash types differ: 73 percent of direct-to-terrain crashes are fully survivable (S=1), compared with 55 percent of the post-obstacle crashes.

- The AH-64 and the UH-60 experience a greater fraction (38 percent) of post-obstacle crashes than the earlier generation of attack and utility helicopters (31 percent). This comparison suggests that the trend is toward a greater frequency of post-obstacle crashes and thus, the 30 percent figure stated above will be a low estimate for current and future activity.

7.4.1 Kinematics

- The cumulative velocity curves recording ground speed (earth reference frame) are very similar for both direct-to-terrain crashes and post-obstacle crashes.
- The cumulative velocity curve recording vertical speed (earth reference frame) for the post-obstacle crashes is higher than the corresponding curve for direct-to-terrain at nearly all percentiles.
- As characterized by the 95th percentile partially survivable crash, the vertical velocity (aircraft reference frame) for the direct-to-terrain crashes is very similar to that in ,the ACSDG'71 at 41 ft/s. The 95th percentile for the post-obstacle crashes is slightly higher at 45 ft/s.
- The 95th percentile longitudinal velocity (aircraft reference frame) for direct-to-terrain partially survivable crashes is 100 ft/s compared to 50 ft/s in the ACSDG'71. The 95th percentile longitudinal velocity for the post-obstacle crashes is lower at 80 ft/s.
- The 95th percentile lateral velocity (aircraft reference frame) for direct-to-terrain partially survivable crashes determined in this study is 18 ft/s. No corresponding value was determined in the ACSDG'71 for comparison. The same parameter for post-obstacle crashes is 28 ft/s.
- Direct-to-terrain crashes occur more frequently with low flight path and low impact angle than do the post-obstacle crashes. In contrast the post-obstacle crashes occur almost twice as often with near vertical flight path and impact angles.
- Consistent with previous studies the attitude angles are tightly clustered around the normal flight attitude (pitch, roll, and yaw = 0).
- The two crash types have different frequency distributions for the attitude angles. The post-obstacle crashes show lower peak frequencies at the zero values, broader distributions and more extreme values. A regression analysis of the angle data confirmed the larger angle variation in the post-obstacle crashes.
- The mean impact severities for the post-obstacle crashes are equal to or higher than the mean impact severities for the direct-to-terrain crashes.
- Sixty-six percent of all crashes occurred on sod. Just 16 percent occurred on prepared surfaces. These relative frequencies remained consistent between both survivable and non-survivable crashes and between crashes directly to terrain and post-obstacle crashes.
- Trees are the most common obstacles associated with crashes. Trees are present in the vicinity of 40 percent of survivable and partially survivable crashes directly-to-terrain. They were present near 72 percent of the post-obstacle crashes.

7.4.2 Other Considerations

- Crashworthy fuel systems have virtually eliminated deaths due to post-crash fires. Only two accidents occurred with multiple deaths due to post-crash fire and both involved non-crashworthy auxiliary fuel systems.
- Protective equipment, lap belts, shoulder harnesses, inertia reels and seats, are widely used by pilots and generally effective. The same equipment is less available, less often used, and less effective (when used) for people in the cabin.

An analysis was conducted to identify the velocity at which the crashes by each aircraft type resulted in severe injuries (fatal or disabled) to all onboard. Above the severe injury transition velocity all occupants experience severe injuries. The severe injury transition velocity can be interpreted as one measure of the crashworthiness of the aircraft.

- The vertical transition velocities for the direct-to-terrain crashes were generally higher than the transition velocities for the post-obstacles crashes of the same aircraft type. The UH-1 and AH-64 were exceptions.
- Grouping the aircraft by rotor system and looking at the vertical transition velocity reveals that the OH-58D with the bearingless rotor system has a much lower transition velocity than the OH-58A/C with a teetering rotor system (28 vs >42 ft/s).
- The UH-60 has the highest vertical transition velocity in the analysis and, as such, could be considered the most crashworthy aircraft by this measure.
- Similar comparisons for the post-obstacle crashes reveal that the OH-58A/C and D have virtually identical transition velocities. This outcome suggests that the transition velocity for these crashes has more to do with the structural integrity and personal protective equipment than the rotor system. This inference is supported by the fact that the transition velocity for the AH-64 is far higher than for the AH-1 and, likewise, the UH-60 is significantly higher than the UH-1.

7.5 Recommendations

Some of the findings in this report suggest that a fundamental re-evaluation of crashworthiness strategy should take place. The current strategy concentrates on vertical energy absorption. The findings in this study indicate that the strategy should be more robust to impacts that occur off the normal aircraft attitude. The fact that 30 percent of the crashes in this study were post-obstacle crashes and that these crashes have significantly lower survivability suggests that the aircraft crashworthiness is less effective in non-vertical events. That the post-obstacle crashes lead to greater variation in the impact attitude suggests that the crashworthiness mitigation technologies should be more robust to non-normal attitude angles. The fact that only 16 percent of crashes occur on prepared surfaces suggests that the mitigation technology should also be robust to variations in the surface stiffness. A shift toward greater design tolerance may lead to less reliance on landing gear for energy absorption with the weight being re-allocated to more robust structure and other means of absorbing energy that are more effective in the lateral directions and on softer surfaces.

The need to reevaluate the approach to crashworthiness is supported by the fact that the current generation aircraft represented by the AH-64 and the UH-60 are experiencing post-obstacle crashes at a frequency of 38 percent, rather than the 30 percent for the whole study population of crashes.

Appendix A References

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Appendix B Acronyms and Abbreviations

Acronyms/Abbreviations

AATD	Aviation Applied Technology Directorate
ACAP	All Composite Airframe Program
ACSDG	Aircraft Crash Survival Design Guide
ADS	Aeronautical Design Standard
AGL	Above Ground Level
AH	Attack Helicopter
ARL	Analytical Readiness Level
ASME	American Society of Mechanical Engineers
ATD	Anthropomorphic Test Dummy
ATRL	Analytical Tool Readiness Level
CABS	Cockpit Airbag Systems
CFIT	Controlled Flight Into Terrain
CH	Cargo Helicopter
CI	Crashworthiness Index
CONOPS	Concept of Operations
DGW	Design Gross Weight
DoD	Department of Defense
DoN	Department of the Navy
DVE	Degraded Visual Environment
ETL	Effective Translational Lift
EU	Engineering Unit
FDR	Flight Data Recorder

FOD	Foreign Object Damage
FSC	Full Spectrum Crashworthiness
HF	Human Factor
HTAWS	Helicopter Terrain (and Obstruction) Awareness Warning System
IARV	Injury Assessment Risk Values
IGE	In Ground Effect
IMC	Instrument Meteorological Conditions
IT	In-flight plus Terrain
JFTL	Joint Future Theater Lift
JMR	Joint Multi-Role
LIDAR	LIght Detection And Ranging
LS-DYNA	Software code developed by LSTC Software, Inc.
M&S	Modeling and Simulation
MFOQA	Military Flight Operations Quality Assurance
NASA	National Aeronautics and Space Administration
NHF	Non-Human Factor
NOE	Nap Of Earth
NRTC	National Rotorcraft Technology Center
NTSB	National Transportation Safety Board
OGE	Out of Ground Effect
OH	Observation Helicopter
RAH	Reconnaissance Attack Helicopter
R&D	Research and Development
RDECOM	Research, Development and Engineering Command
RWSTD	Rotary Wing Structures Technology Demonstration
SARAP	Survivable, Affordable, Repairable, Airframe Program
SEA	Specific Energy Absorption: energy/mass
T	Aircraft impacted only terrain
TA	Terrain after In-flight
TCAD	Terrain Collision Advisory Device
TCAS	Terrain Collision Avoidance System
TRL	Technology Readiness Level
UAV	Unmanned Aerial Vehicles
UET	Underwater Egress Training
UH	Utility Helicopter
US	United States
VEA	Volumetric Energy Absorption**:** energy/volume
V&V	Verification and Validation

APPENDIX C Terms

1.Aborted takeoff

An unplanned event that occurs before intent for flight exists, with engine(s) running, that interrupts a planned flight (except for maintenance test flights and factory acceptance flights).

2.Accident

An unplanned event that causes personal injury or illness, or property damage.

3.Accident and Incident Classes

Army Regulation Reference Appendix A3 defines Class A-D accidents, Class E aviation incident, and Foreign Object Damage (FOD) aviation incident (aka Class F incident). For the purposes of this document, we are only concerned with Classes A-C as defined below.

4.Class A Accident

An accident in which the resulting total cost of property damage is $2,000,000 or more; an aircraft or missile is destroyed, missing, or abandoned; or an injury and/or occupational illness results in a fatality or permanent total disability(Ref Appendix A3).

5. Class B Accident

An accident in which the resulting total cost of property damage is $500,000 or more, but less than $2,000,000; an injury and/or occupational illness results in permanent partial disability, or when three or more personnel are hospitalized as inpatients as the result of a single occurrence(Ref Appendix A3).

6. Class C Accident

An accident in which the resulting total cost of property damage is $50,000 or more, but less than $500,000; a nonfatal injury causes any loss of time from work beyond the day or shift in which it occurred; or non-fatal occupational illness that causes a loss of time from work (for example, 1 work day) or disability at any time (lost time case) (Ref Appendix A3).

7. Aircraft Flight Accident

An accident in which intent for flightexists, and there is reportable damage to the aircraft (not including Unmanned Arial Vehicles (UAVs)). Explosives, chemical agent, or missile events that cause damage to an aircraft with intent for flight are categorized as flight accidents to avoid dual reporting. (IAW the *DoDI 6055.07, October 3, 2000*), DA PAM 385-408. Flight-related Accidents

Those aircraft accidents in which there is intent for flight and no reportable damage to the aircraft itself, but the accident involves a fatality, injury to air crew, ground crew, or passengers, or other property damage. The accidents are not to be used in calculation of flight accident rates. For example repelling accidents, where personnel repelling from aircraft are injured (Ref Appendix A3).

9. Aircraft Flight Related Accident (Non-Flight Rate Producing)

An accident in which there is intent for flight and no reportable damage to the aircraft itself, but the accident involves fatality, reportable injury, or reportable property damage. A missile or UAV that is launched from an aircraft, departs without damaging the aircraft, and is subsequently involved in a DoD Accident is reportable as a Guided Missile Accident or UAV Accident, respectively. (IAW the *DoDI 6055.07, October 3, 2000)*

10. Aircraft Ground Operations Accident (Non-Flight Rate Producing)

An accident in which there is no intent for flight and which results in damage to an aircraft, death or injury. This sub-category applies to aircraft both on land and onboard ship. Damage to an aircraft, when it is being handled as a commodity or cargo, is not reportable as an aircraft accident. (IAW the *DoDI 6055.07, October 3, 2000*)

11. Destroyed aircraft

An aircraft is considered destroyed/total loss when the estimated cost to repair exceeds the current full-up replacement cost.

12. Environmental factors

Environmental conditions which had, or could have had an adverse effect on the individual's actions or the performance of equipment.

13. Flight crew

Personnel on flight pay who are involved in operation of the aircraft.

14. Forced landing

A landing caused by failure or malfunction of engines, systems, or components that makes continued flight impossible.

15. Foreign Object Damage (FOD)

Damage to vehicle/equipment/property as a result of objects alien to the vehicle/equipment damaged. Excludes aircraft turbine engine(s) defined as a FOD incident.

16. Human error

Human performance that deviated from that required by the operational standards or situation. Human error in accidents can be attributed to a system inadequacy/root cause in training, standard, leader, individual, or support failure.

17. Human factors

Human interactions (man, machine, and/or environment) in a sequence of events that were influenced by, or the lack of human activity, which resulted or could result in an accident.

18. Injury

    A traumatic wound or other condition of the body caused by external force, including stress or strain. The injury is identifiable as to time and place of occurrence and member or function of the body affected, and is caused by a specific event or incident or series of events or incidents within a single day or work shift.

19. Intent for flight

    Intent for flight begins when aircraft power is applied, or brakes released, to move the aircraft under its own power with an authorized crew. Intent for flight ends when the aircraft is at a full stop and power is completely reduced.

20. Occupational illness

    Non-traumatic physiological harm or loss of capacity produced by systemic infection; continued or repeated stress or strain; for example, exposure to toxins, poisons, fumes; or other continued and repeated exposures to conditions of the work environment over a long period of time. Includes any abnormal physical or physiological condition or disorder resulting from an injury, caused by long- or short-term exposure to chemical, biological, or physical agents associated with the occupational environment. For practical purposes, an occupational illness is any reported condition which does not meet the definition of an injury.

21. Occupational injury

    A wound or other condition of the body caused by external force, including stress or strain. The injury is identifiable as to time and place of the occurrence and a member or function of the body affected, and is caused by a specific event or incident or a series of events or incidents within a single day or work shift.

22. Permanent total disability

    Any nonfatal injury or occupational illness that, in the opinion of competent medical authority, permanently and totally incapacitates a person to the extent that he or she cannot follow any gainful employment. (The loss of use of both hands, feet, eyes, or any combination thereof as a result of a single accident will be considered as permanent total disability.)

23. Permanent partial disability

    Any injury or occupational illness that does not result in death or permanent total disability but, in the opinion of competent medical authority, results in the loss or permanent impairment of any part of the body, with the following exceptions:

    a. Loss of teeth.
    b. Loss of fingernails or toenails.
    c. Loss of tip of fingers or tip of toe without bone involvement.
    d. Inguinal hernia, if it is repaired.
    e. Disfigurement.
    f. Sprains or strains that do not cause permanent limitation of motion.

24. System inadequacy

A tangible or intangible element that did not operate to standards, resulting in human error or materiel failure. Also, referred to in the Army Regulation 385-40, as causes, readiness shortcomings, and/or root causes.

Appendix D – Example KPPs for Crashworthiness

TBD